

multi-stage purification units such as ecological ditches, ecological ponds, settling zones, and constructed wetlands, this model extends ecological food chain closure from inside a single culture pond to areas beyond the pond, thereby achieving tailwater recycling and advanced purification. In this model, aquaculture tailwater is no longer directly discharged into external water bodies. Instead, it first enters a settling zone or ecological ditch, where reduced flow velocity allows suspended particles, residual feed, and part of the organic detritus to settle. The tailwater then flows through ecological ditches and constructed wetlands planted with aquatic vegetation, where plant uptake, substrate adsorption, microbial degradation, and sedimentation-filtration further reduce nitrogen, phosphorus, organic matter, and suspended solids. Studies on ecological engineering pond aquaculture recirculating systems (EPAS) have shown that, after integrating culture ponds with ecological ditches, ecological ponds, and subsurface-flow constructed wetlands, the average removal rates of ammonia nitrogen, total nitrogen, and total phosphorus in the treatment process can reach 44%~63%, CODMn removal can reach 62%, and chlorophyll a removal can reach 83%, making nutrient and pigment concentrations in culture ponds significantly lower than those in control ponds (Liu et al., 2014).

The advantage of this model lies in its ability to extend ecological regulation from individual ponds to the aquaculture area scale, forming a system pathway of "pond production-tailwater collection-ecological purification-recycling or compliant discharge." Ecological ditches serve as channels for water transport and primary purification, while constructed wetlands undertake advanced purification and ecological buffering functions. Treated water can be reused for pond replenishment according to water quality conditions or discharged into the external environment after meeting discharge requirements, thereby reducing the impact of aquaculture tailwater on surrounding rivers, lakes, and farmland ecosystems. Under the EPAS configuration, unit yield increased from 0.75 kg/m³ to 0.82 kg/m³, and the feed coefficient decreased by 8.2%, indicating that water quality improvement can also enhance aquaculture efficiency (Liu et al., 2014). At larger scales, constructed wetlands used to treat tailwater from inland fish farms or shrimp farms can continuously remove 25%~70% of nitrogen species, more than 60% of phosphorus, and approximately 30%~40% of COD, often bringing total nitrogen, total phosphorus, and COD levels below national discharge standards (Li et al., 2024; Wang et al., 2024).

These multi-stage systems close material cycles through hydraulic retention, plant uptake, microbial transformation, and substrate adsorption/precipitation. Multi-stage surface-flow constructed wetlands composed of different aquatic plants, aeration, and biofiltration membranes can maintain total removal efficiencies above 60% across different seasons, with plant-associated biofilms and changing bacterial communities jointly supporting nitrogen, phosphorus, and organic matter removal. Cases of constructed wetlands based on settling ponds and native reeds have shown that, by optimizing hydraulic conditions, removal rates of organic matter, nutrients, and heavy metals from shrimp farm wastewater can reach as high as 80%~91% while shortening treatment time. Compared with systems that rely solely on internal pond regulation, this model has stronger stability and operability and can help promote freshwater pond aquaculture toward regional management, circular utilization, and green production.

5 Practical Pathways for Ecological Food Chain Closure in Freshwater Pond Aquaculture

5.1 Scientific design of pond ecological structure

The effective operation of ecological food chain closure first depends on the scientific and rational design of pond ecological structure. A freshwater pond is not a single aquaculture water body, but a composite ecosystem composed of multiple spatial units, including the water body, sediment, banks, inlet and drainage systems, plant purification zones, tailwater treatment zones, and ecological ditches. Therefore, the focus of pond ecological structure design lies not only in determining the size and shape of the aquaculture water surface, but also in systematically organizing the spatial pattern and hydraulic processes, so that water, nutrients, and pollutants can sequentially pass through multiple functional units such as production, sedimentation, absorption, decomposition, and purification before discharge or recycling. In practice, pond functional zones should be reasonably divided according to pond area, water depth, sediment type, water source conditions, main cultured species, and