

layers, as well as the water column, sediment, and plant zones. For example, herbivorous or omnivorous fish can utilize some plant-based feed and organic detritus; filter-feeding fish and shellfish can utilize plankton and suspended particles; detritivores can process benthic wastes; aquatic plants and macroalgae can absorb dissolved nutrients and improve habitat conditions; and microbial consortia support the transformation of carbon, nitrogen, phosphorus, and other elements (Biswas et al., 2020; Tang et al., 2024). This niche complementarity enables materials and energy in ponds to cascade through multiple trophic levels, thereby improving system resource utilization efficiency.

IMTA and polyculture studies consistently show that, compared with monoculture or simple polyculture, combining fed species such as fish and shrimp with detritivores, filter feeders, and primary producers can increase total productivity, improve individual growth and survival, and simultaneously reduce environmental impacts. For example, combinations such as shrimp-fish-bivalve-seaweed or giant freshwater prawn-carp-mussel can suppress cyanobacterial blooms, enhance beneficial microorganisms in sediments, reduce nitrogen and phosphorus emissions in tailwater by 50%~60%, and achieve higher productivity indices and profitability (Biswas et al., 2020; Tang et al., 2024). Ecosystem models and dynamic energy budget models of three-trophic-level IMTA systems further confirm that properly balanced stocking densities can reduce waste concentrations while maximizing multispecies yield, indicating that food-web design and density optimization are central to achieving trophic synergy. Therefore, by reasonably controlling the proportions of main cultured species, companion species, and purification organisms, freshwater ponds can form composite aquaculture systems that integrate production, purification, and ecological regulation functions, thereby achieving the coordinated goals of yield enhancement, environmental improvement, and risk reduction.

4 Typical Application Models of Ecological Food Chain Closure in Freshwater Ponds

4.1 Fish-shrimp-shellfish-algae coordinated aquaculture model

The fish-shrimp-shellfish-algae coordinated aquaculture model is a representative multi-trophic utilization model in ecological food chain closure in freshwater ponds. In essence, it is the pond-based application of integrated multi-trophic aquaculture (IMTA). This model combines fed species, such as fish and shrimp, with extractive species, such as bivalves, seaweeds, or macroalgae, so that feed, plankton, organic detritus, and dissolved nutrients in ponds can be utilized across different levels. In such systems, fish and shrimp consume formulated feed and form the main economic output, while also producing particulate and dissolved wastes. Shellfish reduce water turbidity and regulate plankton abundance by filtering phytoplankton, bacterial flocs, and suspended particles. Algae or macrophytes, as primary producers, can absorb dissolved nutrients such as nitrogen and phosphorus and also provide a natural food base for filter-feeding organisms. Existing studies have shown that combining fish and shrimp with extractive organisms such as shellfish and algae can transform waste nutrients into additional biomass and improve aquaculture water quality (Biswas et al., 2020; Chang et al., 2020; Thomas et al., 2020; Tang et al., 2024).

During the operation of this model, external feed is first consumed by fish and shrimp. Uneaten feed and excreta from cultured animals then enter the water column and can promote the growth of algae and microorganisms. An appropriate amount of algae can increase dissolved oxygen through photosynthesis and provide food for filter-feeding fish and shellfish, while filter-feeding organisms can in turn control excessive algal proliferation and reduce the risk of algal blooms. Shrimp and some benthic animals can utilize organic detritus deposited at the pond bottom, thereby reducing the organic load in sediment. Thus, a circular chain of "feed input-fish and shrimp growth-organic matter release-algal transformation-reuse by shellfish and filter feeders" is formed within the pond. In brackish or low-salinity pond trials, combinations of shrimp, fish, oysters, and water spinach or seaweeds significantly reduced inorganic nitrogen and phosphorus levels, improved dissolved organic carbon utilization, and enhanced shrimp growth performance (Biswas et al., 2020).

In experimental IMTA ponds, combinations of shrimp, milkfish, mussels, and *Gracilaria* showed significantly higher specific growth rates, survival rates, and combined biomass of shrimp and fish than monoculture or simple