

2 Basic Connotations and System Composition of Ecological Food Chain Closure

2.1 Conceptual definition of ecological food chain closure

Ecological food chain closure refers to the rational configuration of different functional organisms, such as producers, consumers, and decomposers, within a defined aquaculture space according to the principles of material cycling, energy flow, and trophic complementarity in ecosystems. Through this configuration, major outputs generated during aquaculture, including residual feed, feces, organic detritus, sludge, tailwater, and dead organisms, can be collected, transformed, and reintegrated into production pathways within the system, thereby minimizing direct discharge, landfill disposal, and nutrient loss. Compared with traditional pond aquaculture characterized by single-species culture, high feed input, and high discharge, ecological food chain closure places greater emphasis on functional complementarity among biological groups within the aquaculture system. By constructing relatively complete food chains, decomposition chains, and purification chains, wastes that might otherwise become pollution sources can be transformed into reusable ecological resources, thereby reducing waste accumulation and discharge pressure. Relevant studies have shown that zero-waste and circular aquaculture models can integrate closed ponds, composting treatment, and plant production, allowing nutrients in fish aquaculture wastewater and sludge to be valorized, thereby improving productivity and reducing operating costs (Lothmann and Sewilam, 2022; Nenciu et al., 2022). Closed ecological recirculating aquaculture systems also couple biological components such as phytoplankton, zooplankton, and fish to achieve internal CO₂- O₂ circulation and nutrient reuse within the system (Takeuchi, 2017).

From the perspective of operational logic, ecological food chain closure is not simply about increasing the number of polyculture species; rather, it establishes systematic connections around the process of "resource input-biological utilization-waste transformation-nutrient reuse-product output." After feed input, part of the nutrients is directly consumed by the main cultured animals and converted into aquaculture products, while residual feed, feces, and metabolic wastes that are not fully utilized can re-enter the food chain through microbial decomposition, aquatic plant uptake, plankton transformation, and re-feeding by filter-feeding or omnivorous animals. In this way, pond aquaculture systems can gradually shift from a one-way consumption structure to a circular utilization structure. In aquaculture practice, recirculating aquaculture systems (RAS), aquaponic systems, biofloc technology, and integrated multi-trophic aquaculture (IMTA) all demonstrate closed-loop characteristics by strengthening nutrient cycling, reducing tailwater discharge, and improving resource utilization efficiency. At the ecosystem level, integrated pond and IMTA models show that the introduction of filter feeders, macroalgae, or other functional cultured species can enhance the utilization of primary productivity and detrital resources, improve energy transfer efficiency, and increase system maturity and stability (Dong et al., 2022; Zhang et al., 2024). Therefore, "closure" is both a physical attribute, referring to reduced discharge and external losses, and a functional attribute, referring to improved internal recycling efficiency and energy utilization.

2.2 Main functional units of freshwater pond ecosystems

Freshwater pond ecosystems can be regarded as relatively small and simplified artificial-natural composite ecosystems. Although their food chains are relatively short, they contain structured functional groups. The main functional units include producers, consumers, and decomposers. Producers mainly include phytoplankton, periphyton, submerged plants, emergent plants, macrophytes, and plants on artificial ecological floating beds. They fix energy through photosynthesis and absorb nutrients such as nitrogen and phosphorus from the water, serving as an important foundation for maintaining pond ecological balance. Consumers include the main cultured fish, shrimp and crabs, shellfish, filter-feeding fish, omnivorous fish, benthic invertebrates, and zooplankton. These organisms occupy different water layers and ecological niches and utilize formulated feed, plankton, organic detritus, and benthic resources in different ways. Ecopath-based pond studies generally divide pond systems into components such as primary producers, zooplankton of different size classes, benthic invertebrates, bacteria in water and sediment, detritus pools, and cultured fish and invertebrates at lower trophic levels (Zhang et al., 2024). In integrated aquaculture ponds, clams or other filter feeders usually occupy the second trophic level and can directly utilize phytoplankton and detritus, thereby altering the overall energy flow pathway of the system (Dong et al., 2022).