

Decomposers are mainly composed of bacteria, fungi, and other microbial communities and serve as indispensable transformation links in ecological food chain closure in ponds. They decompose residual feed, feces, dead organisms, and organic matter in sediment, transforming complex organic matter into inorganic nutrients that can be absorbed and utilized by plants and algae, and they play key roles in carbon, nitrogen, and phosphorus cycling. Meanwhile, sediment, water bodies, ecological ditches, constructed wetlands, biofilm substrates, and aeration facilities can also be regarded as important supporting units for system operation. Together, these units affect dissolved oxygen, pH, transparency, sediment condition, nutrient concentration, and microbial community structure in the water, thereby determining whether the ecological closed-loop system can operate stably. It should be noted that the functional units in freshwater pond ecosystems are not static; rather, they are strongly influenced by aquaculture management. Intensive or integrated aquaculture ponds are usually under a high degree of artificial control, and feed input, mechanical aeration, water exchange regulation, and water quality management can alter trophic relationships and internal system structure (Zhang et al., 2024). Studies have also shown that zooplankton and macrozooplankton are often important functional groups affecting energy transfer, whereas detritus and associated bacteria in the water and sediment are important nodes of system throughput, frequently receiving large amounts of unused feed, feces, and dead biomass. These materials may become pollution loads, but they can also be reintroduced into the food chain through appropriate species or ecological substrates (Dong et al., 2022).

### 2.3 Material cycling and energy flow in closed-loop systems

In ecological food chain closure in freshwater ponds, material cycling mainly involves the transformation of carbon, nitrogen, phosphorus, and organic matter. Aquaculture feed is the main source of external material input into the system. After the main cultured animals consume feed, part of the nutrients is converted into biomass, while the remaining portion enters the water column and sediment in the form of residual feed, feces, and metabolic products. Microorganisms decompose these organic substances and release nutrients such as ammonia nitrogen and phosphate, which are then absorbed and utilized by algae, aquatic plants, and constructed wetland plants. Some of these nutrients are further converted into new aquaculture products through zooplankton, filter-feeding fish, shellfish, and benthic animals. The goal of closed-loop aquaculture is to maximize the internal cycling of nutrients and energy while minimizing their loss to the environment. Ecopath analyses of integrated ponds show that most primary production and energy usually flow into detritus pools, but the introduction of additional species such as clams and filter-feeding fish can significantly increase the proportion of primary productivity and detritus flowing to the second trophic level and harvestable biomass. Ecosystem indicators such as Finn's cycling index and mean path length usually increase in integrated aquaculture systems, indicating that, compared with monoculture systems, integrated systems have higher internal recycling levels, greater maturity, and stronger resistance to disturbance (Figure 1) (Dong et al., 2022; Zhang et al., 2024).

Energy flow begins from primary energy sources such as feed, algae, and aquatic plants and is transferred stepwise along different trophic levels. Because energy is continuously lost during transfer, the key objective of closed-loop systems is not to achieve complete energy recovery, but to maximize utilization efficiency among different trophic levels and reduce resource waste and pollution accumulation. For example, filter-feeding fish and shellfish can utilize plankton and suspended particles, benthic animals can utilize deposited organic detritus, aquatic plants can absorb dissolved nutrients, and microorganisms and biofilms can promote organic matter degradation and nutrient regeneration. Technological and management innovations further strengthen these biological cycles. Studies have shown that ecological substrates that support biofilm formation can increase food-web pathways by more than 25%, improve detritus utilization by approximately 15%, and enhance energy transfer efficiency and system stability (Zhang et al., 2024). Recirculating aquaculture systems and aquaponic systems achieve water circulation through mechanical and biological filtration, sometimes with the addition of wetland or algae units. In such systems, nutrient-rich tailwater can be used to irrigate crops or cultivate macroalgae, thereby closing water and nutrient cycles and reducing eutrophication potential (Lothmann and Sewilam, 2022; Nenciu et al., 2022). Life cycle assessments also indicate that when feed, energy use, and by-product utilization are optimized, closed-loop systems can reduce water consumption, nutrient emissions, and overall environmental burdens per unit of food produced. Therefore, material cycling and energy flow in