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Application Mechanisms and Practical Pathways of Ecological Food Chain Closure in Freshwater Pond Aquaculture

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Abstract Freshwater pond aquaculture is an important component of China' s aquaculture system. However, long-term high-density feeding and intensive management can easily lead to the accumulation of residual feed, feces, organic detritus, and nutrients in the water column and sediment, resulting in water quality deterioration, sediment aging, eutrophication, and increased pressure from tailwater discharge. Ecological food chain closure is based on material cycling, energy flow, and trophic complementarity. By rationally configuring producers, consumers, and decomposers, aquaculture wastes can be reintroduced into the internal circulation of pond ecosystems, thereby achieving resource reuse and pollution reduction. This study explores the application mechanisms and practical pathways of ecological food chain closure in freshwater pond aquaculture, elaborates its roles in nutrient recycling, water self-purification regulation, and multi-trophic synergistic enhancement, and summarizes typical models including fish-shrimp-shellfish-algae coordinated aquaculture, fish-aquatic plant-microorganism ecological regulation, and pond-ecological ditch-constructed wetland recycling purification. The study suggests that ecological food chain closure can improve pond resource utilization efficiency, enhance water self-purification capacity, reduce pressure from tailwater treatment, and promote the transformation of aquaculture systems from high-input and high-discharge models toward ecological, circular, and efficient development. However, its promotion still faces challenges such as unreasonable biological configuration, fluctuations in environmental conditions, insufficient technical management capacity, and incomplete economic evaluation systems. In the future, green and sustainable development of freshwater pond aquaculture should be promoted through site-specific model selection, optimization of aquaculture species and trophic-level configuration, improvement of water quality monitoring and tailwater recycling systems, and strengthening of standardized and digital management.

Keywords Ecological food chain closure; Freshwater pond aquaculture; Nutrient cycling; Water self-purification; Green aquaculture

1 Introduction

Freshwater pond aquaculture is an important component of China's aquaculture system and also a major supporting form of global aquatic food production. It plays an important role in ensuring the supply of aquatic products, increasing farmers' income, and promoting the development of rural industries. In countries with large-scale freshwater aquaculture, such as China, pond aquaculture accounts for a substantial proportion of total aquatic product output. However, with the rapid intensification of pond aquaculture, traditional production methods that rely on manual feeding, mechanical aeration, frequent water exchange, and pharmaceutical disease control have increased yield per unit area to some extent, but they have also intensified the dependence of aquaculture systems on external inputs such as feed, water resources, energy, and drugs. As stocking density and feed input increase, residual feed, feces, dead algae, and other organic matter continuously accumulate in the water column and sediment, easily leading to increases in ammonia nitrogen, nitrite, total nitrogen, and total phosphorus. This, in turn, results in water quality deterioration, sediment aging, eutrophication, frequent disease outbreaks, and increased pressure from tailwater discharge. These problems not only constrain the sustainable development of freshwater pond aquaculture but may also adversely affect surrounding water bodies and ecosystems (Boyd et al., 2020; Liu et al., 2020; Duan et al., 2024). Meanwhile, the growing demand for green, low-carbon, and environmentally friendly food systems is driving pond aquaculture to shift from a high-input, high-consumption, and pollution-emitting model toward a resource-saving, ecologically efficient, and circular utilization model (Henares et al., 2020; Zhong et al., 2022; Dong et al., 2025).

The green transformation of freshwater pond aquaculture is both a practical need for environmental protection and an important opportunity for high-quality industrial development. Relevant studies have shown that, during the long-term intensive expansion of pond aquaculture in China, pond water quality once showed a declining trend, whereas the promotion of ecological engineering, ecological aquaculture practices, and green policy measures has helped improve pond water environments (Liu et al., 2020; Duan et al., 2024). Eco-efficiency assessments also indicate that freshwater aquaculture still faces redundant inputs and pressure from pollutant emissions, suggesting considerable room for improving resource use efficiency and reducing pollution discharge while maintaining economic benefits (Zhong et al., 2022; Dong et al., 2023). Against this background, ecological engineering pathways such as integrated multi-trophic aquaculture, pond cascade systems, planted oxidation ponds, bio-integrated aquaponic systems, and aquaculture-agriculture integrated systems have gradually attracted attention and are regarded as important technical directions for coordinating aquaculture production with environmental protection (Henares et al., 2020; Thomas et al., 2020; ong et al., 2022; Lothmann and Sewilam, 2022; D Kajgrová et al., 2023; Goda et al., 2024).

In the process of green transformation of freshwater pond aquaculture, the concept of ecological food chain closure provides a new approach for optimizing aquaculture systems. Ecological food chain closure refers to the establishment of relatively stable material cycling and energy flow relationships within pond ecosystems through the rational allocation of producers, consumers, and decomposers. In this process, residual feed, feces, and organic detritus generated after feed input can be decomposed by microorganisms, absorbed by algae and aquatic plants, and further reused by filter-feeding fish, omnivorous fish, benthic animals, and other organisms at different trophic levels. Existing studies have shown that combining fed fish with detritivores, filter feeders, macrophytes, and vegetables can improve feed conversion efficiency, increase nitrogen and phosphorus retention, and transform aquaculture waste into additional biomass (Thomas et al., 2020; Dong et al., 2022; Kajgrová et al., 2023; Goda et al., 2024). Therefore, ecological food chain closure does not simply mean increasing the number of cultured species; rather, it emphasizes the complementarity among different biological groups in terms of ecological niches, feeding targets, spatial distribution, and functional roles. Integrated multi-trophic aquaculture in freshwater and marine systems, pond cascade systems, and aquaculture-agriculture integrated models all indicate that strengthening internal food webs, promoting nutrient recycling, and reducing dependence on external water exchange can improve resource use efficiency and generate diversified products (Henares et al., 2020; Lothmann and Sewilam, 2022). Ecological food chain closure not only helps improve nutrient recycling efficiency by converting residual feed and metabolic wastes that might otherwise become pollution sources into ecological resources that can be reused within the system, but also enhances pond self-purification capacity through nitrogen and phosphorus uptake by aquatic plants, organic matter degradation by microorganisms, phytoplankton regulation by filter feeders, and sediment improvement by benthic animals, thereby reducing disease risks and pressure from tailwater treatment.

This study will explore the application mechanisms and practical pathways of ecological food chain closure in freshwater pond aquaculture. In response to the demand for green transformation in freshwater pond aquaculture, it systematically analyzes the basic connotations, system composition, and operational logic of ecological food chain closure; focuses on its mechanisms in nutrient cycling, water self-purification regulation, and multi-trophic synergistic enhancement; and further examines its implementation pathways in production practice by considering typical models such as fish-shrimp-shellfish-algae coordinated aquaculture, fish-aquatic plant-microorganism ecological regulation, and pond-ecological ditch-constructed wetland recycling purification. Through an analysis of ecological structure design, aquaculture species configuration, water quality monitoring, tailwater recycling, and standardized management, this paper aims to provide theoretical references and practical guidance for the green, ecological, and efficient development of freshwater pond aquaculture.

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 CO_2- O_2 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).

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 closed-loop freshwater ponds essentially integrate pond ecological structure, trophic configuration, and circular economy principles, providing a basis for water quality improvement, yield enhancement, and green aquaculture.

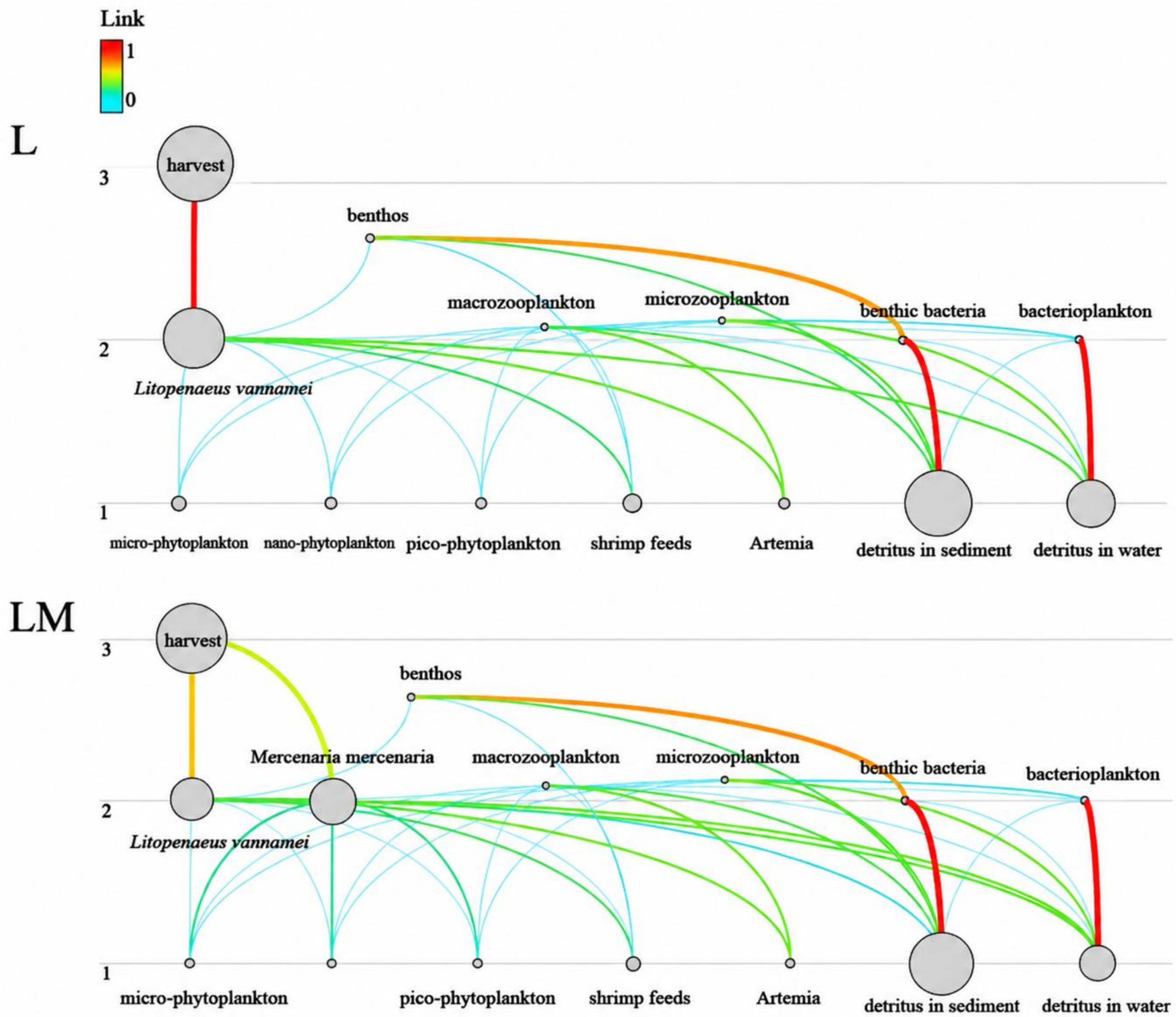

Figure 1 Trophic relationships between functional groups in the two aquaculture ecosystems (Adopted from Dong et al., 2022)
Image caption: L-a monoculture system of *L. vannamei*; LM-an integrated aquaculture system of *L. vannamei* with *M. mercenaria*. Each circle represents the corresponding functional group, the connecting line represents the energy transfer process, and the circle size represents the biomass volume of each group (Adopted from Dong et al., 2022)

3 Application Mechanisms of Ecological Food Chain Closure in Freshwater Pond Aquaculture

3.1 Nutrient recycling and utilization mechanism

In freshwater pond aquaculture, feed input is the main source through which nutrients such as nitrogen (N) and phosphorus (P) enter the system. After cultured organisms such as main cultured fish, shrimp, and crabs consume feed, part of the nutrients is converted into body biomass and eventually forms aquatic products; the remaining part enters the water column and sediment in the form of residual feed, feces, metabolic products, and dead organisms. If these materials cannot be transformed and utilized in a timely manner, they will continuously accumulate in the pond, causing increases in ammonium nitrogen, nitrite, total nitrogen, and total phosphorus, which further leads to water quality deterioration, eutrophication, and increased disease risk. Relevant studies have shown that a considerable proportion of input nitrogen and phosphorus in traditional ponds accumulates in sediments or is discharged with tailwater, resulting in low nutrient utilization efficiency and increasing the risk of ammonium nitrogen and nitrite accumulation (Zhang et al., 2024). Enzyme activity in sediments and coupled nitrogen-phosphorus cycling can regenerate large amounts of dissolved inorganic nutrients; if these nutrients cannot be effectively absorbed and utilized by biota, they will further aggravate water eutrophication and aquaculture disease risks (Bai et al., 2022). Therefore, one of the core functions of ecological food chain closure is to reincorporate these potentially polluting nutrients into the internal cycling of the pond-farm system, transforming them from "wastes" into reusable ecological resources.

Ecological food chain closure realizes nutrient cycling through the multi-stage process of "microbial decomposition-plant uptake-animal reuse." Microbial communities first decompose residual feed, feces, and organic detritus, converting complex organic matter into inorganic nutrients such as ammonia nitrogen and phosphate. Phytoplankton, aquatic plants, and artificial floating-bed plants further absorb nitrogen, phosphorus, and other nutrients in the water, thereby reducing the risk of eutrophication. Zooplankton, filter-feeding fish, shellfish, and benthic animals can then utilize algae, suspended particles, and deposited organic matter, converting low-level resources into harvestable biomass. Model analyses and budget assessments show that macrophytes and other primary producers can contribute more than half of nitrogen and phosphorus retention, indicating that plant and microbial components play key roles in closed nutrient cycling (Campanati et al., 2021; Zhang et al., 2024).

Ecological engineering and integrated multi-trophic aquaculture (IMTA) further restructure nutrient cycling pathways, allowing feed residues and excreta to be gradually transformed and absorbed by multiple biological sinks. For example, in freshwater IMTA-aquaponic systems, fed fish convert part of dietary nitrogen and phosphorus into biomass, detritivores and filter feeders recover nutrients from particulate matter, and macrophytes and hydroponic vegetables assimilate dissolved nutrients, increasing overall nitrogen and phosphorus utilization efficiency to more than 80%~90% and significantly reducing discharge (Figure 2) (Campanati et al., 2021; Goda et al., 2024). Microalgae-bacteria consortia, biofilms, and functional microbial groups involved in nitrification, denitrification, and organic phosphorus hydrolysis are important foundations supporting this cycling process. They can transform toxic forms of nitrogen into biomass or inert end products while providing material support for organisms at higher trophic levels (Biswas et al., 2020).

3.2 Water self-purification and ecological regulation mechanism

Ecological food chain closure can enhance the water self-purification capacity of freshwater ponds. The key lies in the coordinated configuration of hydraulic processes, habitat structures, and biological components, which enables pollutants to be intercepted, settled, absorbed, and transformed along the water flow pathway. Aquatic plants absorb nutrients such as nitrogen and phosphorus through their roots, stems, leaves, and associated microorganisms, while also providing attachment substrates and habitats for microorganisms and small aquatic animals, thereby helping stabilize the ecological structure of the water body. Phytoplankton can release oxygen through photosynthesis, but excessive proliferation may cause algal blooms and diel fluctuations in dissolved oxygen; therefore, filter-feeding fish, shellfish, and zooplankton are needed for moderate regulation to maintain algal abundance within a relatively reasonable range. Cascade pond systems, ecological engineering pond aquaculture systems, and recirculating pond systems equipped with ecological ponds usually employ sequential structures such as ditches, settling units, vegetated zones, biofilm-rich purification ponds, and culture ponds to progressively remove ammonia nitrogen, total nitrogen, total phosphorus, organic matter, and phytoplankton (Liu et al., 2014). Relevant measurements show that the removal rates of total nitrogen and total phosphorus in such systems often exceed 40%~60%, and chlorophyll a and chemical oxygen demand are also significantly reduced, allowing culture ponds to maintain lower nutrient and algal levels than conventional ponds under similar or even higher production conditions (Biswas et al., 2020).

Microorganisms play a fundamental role in water purification and ecological regulation. Beneficial microbial communities can promote organic matter degradation, participate in nitrification, denitrification, and sediment remediation, and reduce the accumulation of harmful substances such as ammonia nitrogen, nitrite, and hydrogen sulfide. High-throughput sequencing studies have shown that Proteobacteria, Actinobacteria, Bacteroidetes, Cyanobacteria, and specialized denitrifying genera are dominant in engineering ponds, IMTA systems, and recirculating ponds. As system operation time increases, improvements in microbial diversity and functional gene abundance are usually associated with water quality improvement. Meanwhile, seagrass or macrophyte reservoirs and constructed wetlands can filter suspended solids, store nutrients in plant biomass, regulate dissolved oxygen through photosynthesis, and reduce pathogen loads, thereby pretreating and purifying pond inflow or tailwater (Liu et al., 2014; Biswas et al., 2020). While feeding on deposited organic detritus, benthic animals can disturb sediment through their activities, improving bottom-water exchange and sediment permeability. Engineering units such as aeration facilities, ecological ditches, and constructed wetlands further strengthen water circulation, sedimentation filtration, and plant uptake functions. As a result, pond systems no longer rely solely on frequent water exchange and chemical regulation, but instead maintain water quality stability and ecological balance through the integration of biological purification, microbial transformation, and engineering regulation.

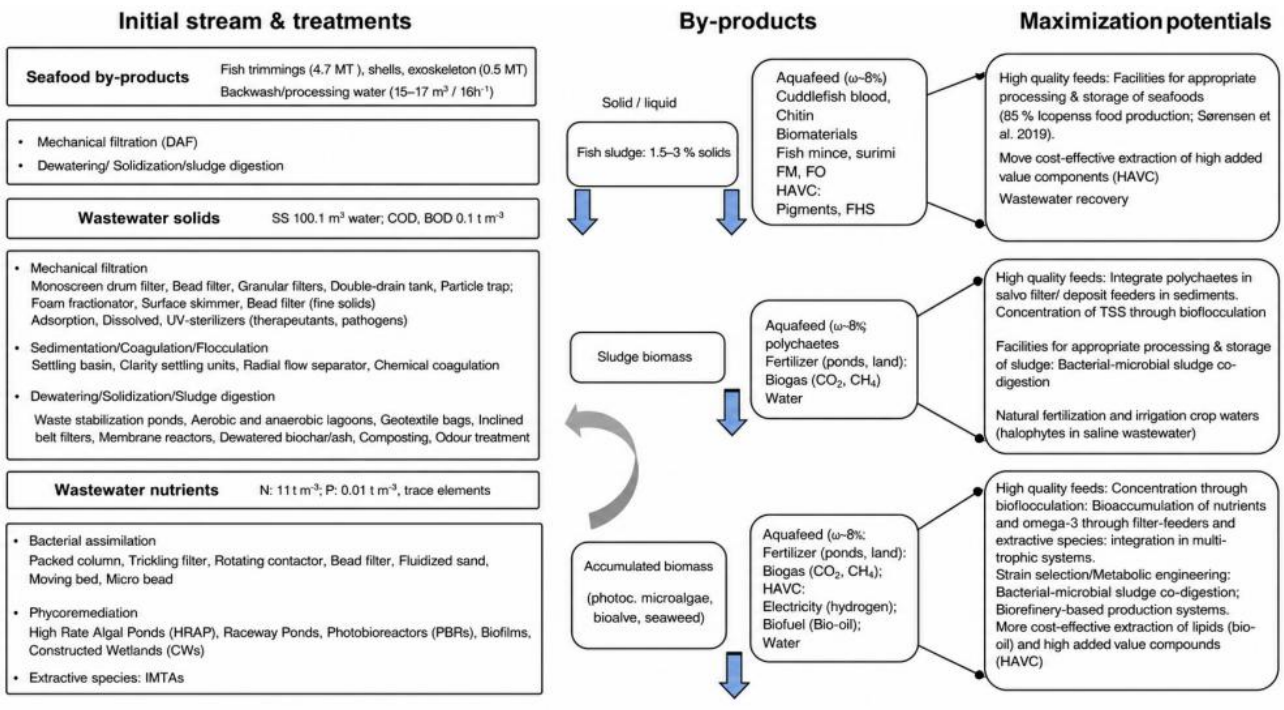

Figure 2 Potential co-products derived from the processing of seafood and wastewater treatments (Adopted from Campanati et al., 2021)

Image caption: Solid material from wastewaters is retained through mechanical filtration and/or sedimentation. Dissolved nutrients are retrievable from wastewater through bacterial assimilation and phytoremediation and can be upcycled (i.e. through increased yield in biomass) throughout the food web (e.g. IMTAs). Following removal of large solids and accumulated suspended material (i.e. TSS, biofloc, microalgae) in concentrated sludge form, dewatering and thickening then permit by-products to be obtained through different recovery paths and allow subsequent applications. Through this process of solid-liquid separation, the water discarded or generated from the processing (light-blue arrows) can be reused. Improvements that can maximize production (e.g. cost-effective methods for higher biomass yield) from recycled materials are highlighted on the right side of the diagram. DAF: Dissolved air floatation; FM: Fish meal; FO: Fish oil; HAVC: High added value components; PHs: Protein hydrolysate (Adopted from Campanati et al., 2021)

3.3 Multi-trophic synergistic enhancement mechanism

Multi-trophic synergy is an important basis for the comprehensive benefits of ecological food chain closure and is also the key mechanism distinguishing it from traditional monoculture or simple polyculture. Traditional single-species aquaculture often focuses on the utilization of a particular type of feed resource or water-layer space, which easily leads to insufficient resource use, unused ecological niches, and pollutant accumulation. In contrast, ecological food chain closure combines organisms according to their feeding habits, activity layers, and ecological functions, enabling effective use of different spaces, including the upper, middle, and bottom water 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 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 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 production objectives, forming a spatial pattern in which the main culture zone, ecological buffer zone, plant purification zone, sedimentation zone, and tailwater collection and treatment zone are interconnected.

Ecological engineering practices in China indicate that eco-engineered pond recirculating systems generally integrate ecological ditches, ecological ponds, subsurface-flow constructed wetlands, and culture ponds to control water replenishment, regulate algal communities, and improve water quality (Liu et al., 2020). In these systems, constructed wetlands and ecological ditches can reduce harmful algal groups and increase the proportion of diatoms, thereby optimizing phytoplankton structure while removing nitrogen and phosphorus from tailwater (Liu et al., 2020). In the design of pond ecological structure, attention should also be paid to water-layer utilization, habitat diversity construction, and spatial planning at the regional scale. Different cultured organisms vary in their use of water space, and the upper, middle, and bottom water layers, as well as nearshore shallow-water areas, can all undertake different ecological functions. For example, the main cultured fish mainly provide economic output, aquatic plant zones are responsible for nutrient uptake and ecological buffering, sediment remediation zones undertake organic matter sedimentation and microbial decomposition, and ecological ditches and sedimentation zones provide preliminary tailwater purification. Through spatial zoning and functional allocation, niche conflicts among different organisms can be reduced, internal resource utilization efficiency in ponds can be improved, and system stability can be enhanced.

Pond cascade systems represent another important structural pathway. Through a series of interconnected ponds managed by batch discharge and refilling, they can achieve strong self-purification, reducing total phosphorus and total nitrogen in the terminal pond to approximately half of their initial concentrations, while supporting advanced fry production and multiple stocking-harvesting cycles (Kajgrová et al., 2023). At a broader scale, ecosystem-based spatial planning and functional zoning help arrange ponds rationally within watersheds, enabling them to meet ecological and social carrying capacity requirements while coordinating biosecurity, water resource management, and disease management among clustered farms. Remote-sensing assessments also show that pond siting, density, and the conversion of surrounding habitats affect sustainability at the landscape scale; therefore, scientifically determining the location and spatial configuration of pond areas is an important prerequisite for constructing ecological food chain closure.

5.2 Optimization of aquaculture species and trophic-level configuration

The key to constructing ecological food chain closure lies in optimizing aquaculture species combinations so that different organisms form complementary relationships in feeding habits, activity layers, and ecological functions. Traditional pond aquaculture often centers on a single main cultured species, which can easily lead to insufficient feed resource utilization, accumulation of residual feed and feces, and increased pressure on water quality regulation. Ecological closed-loop aquaculture should, on the basis of clearly identifying the main cultured species, reasonably combine functional organisms such as filter-feeding fish, omnivorous fish, benthic animals, aquatic plants, and beneficial microorganisms, so that formulated feed, plankton, organic detritus, and dissolved nutrients can be utilized stepwise by different trophic levels. This can improve comprehensive output per unit water body and reduce the impact of aquaculture wastes on water quality and sediment conditions. Studies on ecological engineering and fish polyculture have shown that, compared with single-species intensive ponds, polyculture systems based on species' ecological niches and feeding habits can significantly improve nitrogen utilization, energy conversion efficiency, and environmental performance. Cases of traditional multi-pond shrimp systems in China combined with bivalves and macroalgae have also shown higher equivalent shrimp output and increased input nitrogen utilization by more than 80%, indicating that carefully designed multi-trophic combinations have strong potential for nutrient recovery (Liu et al., 2020).

In specific configuration, the principles of "moderate polyculture, functional complementarity, and controllable density" should be followed. The stocking density of the main cultured species should match the carrying capacity of the pond and should not exceed the regulatory capacity of the ecosystem in pursuit of high yield. Companion species should be selected according to their ecological functions: filter-feeding fish can be used to regulate plankton and suspended particles, benthic animals to utilize deposited organic detritus, aquatic plants to absorb nitrogen and phosphorus and improve habitats, and beneficial microorganisms to promote organic matter decomposition and sediment remediation. Meanwhile, feed input, aeration intensity, and biological configuration ratios should be dynamically adjusted according to seasonal changes, culture stages, and water quality conditions, so as to avoid system imbalance caused by excessive proliferation or insufficient function of a particular organism group. Recent freshwater IMTA studies using combinations of giant freshwater prawn, silver carp, bighead carp, and freshwater pearl mussels have shown that appropriate species combinations can suppress cyanobacterial blooms, increase beneficial sediment microorganisms, reduce phosphorus emissions in tailwater by approximately 60%, and improve nitrogen and phosphorus utilization rates by approximately 11%~13%. However, trade-offs such as high mussel mortality or inhibited growth of cyprinid fish also indicate that multi-trophic configuration still needs to be optimized according to density, species adaptability, and system carrying capacity (Tang et al., 2024).

In addition to empirical trials, species screening and compatibility pre-assessment tools can also support the design of ecological food chain closure. The AquaDesign assistant uses ecological niche hypervolumes and global abiotic environmental data to identify suitable environmental conditions for candidate species and determine whether different species combinations can coexist under shared abiotic environments in ponds, raceways, and recirculating systems (Butruille et al., 2022). Conceptual frameworks for polyculture design also emphasize species compatibility and complementarity and propose a stepwise procedure from candidate species screening, matching with culture environments, and management tool development to stakeholder collaboration (Thomas et al., 2020). In addition, analyses of "trophic level" in aquaculture caution against simply promoting nominally low-trophic species, because the effective trophic level is a property of the entire aquaculture system and is jointly influenced by feed sources, management practices, and system operational efficiency. Therefore, sustainability assessment should be based on actual feed use, management practices, and system performance. These insights collectively indicate that species configuration for ecological food chain closure should shift from "increasing species number" to "matching ecological functions" and "optimizing system efficiency."

5.3 Improvement of water quality monitoring and tailwater recycling systems

Water quality monitoring is an important support for ensuring the stable operation of ecological food chain closure. Freshwater pond ecosystems are characterized by obvious dynamic changes. Indicators such as water temperature, dissolved oxygen, pH, ammonia nitrogen, nitrite, total nitrogen, total phosphorus, transparency, turbidity, and conductivity are all affected by weather, feeding, stocking density, microbial activity, and algal changes. Without continuous monitoring and timely regulation, ecological closed-loop systems may lose balance due to hypoxia, excessive algal proliferation, sediment deterioration, or pollutant accumulation. Therefore, a management mechanism combining daily pond inspection, regular testing, and early warning of key indicators should be established to track water quality trends in a timely manner and adopt measures such as aeration, water exchange, feed control, sediment remediation, beneficial microbial supplementation, or adjustment of plant coverage based on monitoring results. In recent years, recirculating aquaculture systems (RAS) and pond-RAS hybrid systems have relied on mechanical and biological treatment units to remove particulate matter, nitrogen pollutants, phosphorus, carbon dioxide, antibiotics, and other hazardous substances, returning purified water to culture ponds or facilities and thereby greatly reducing overall water use and pollutant discharge (Liu et al., 2020).

Case studies have shown that tailwater purification ponds in ecological RAS can reduce antibiotic concentrations in aquaculture water by more than half, while recirculating systems can achieve more than 80% ammonia nitrogen removal and more than 70% phosphate removal, bringing multiple water quality parameters within recommended limits (Shi et al., 2022). Regarding tailwater utilization, pond drainage should be incorporated into the overall circulation system to avoid direct discharge of untreated aquaculture tailwater. Facilities such as sedimentation ponds, ecological ditches, constructed wetlands, ecological purification ponds, and plant purification belts can be built to achieve graded reduction of suspended solids, organic matter, nitrogen and phosphorus nutrients, antibiotic residues, and other potential pollutants in tailwater. Treated water can be reused for pond replenishment, irrigation of surrounding farmland, or compliant discharge according to water quality conditions, thereby improving water resource utilization efficiency and reducing pressure on surrounding aquatic environments. Reviews of tailwater pollution control in large-scale aquaculture emphasize that constructed wetlands, ecological ditches, IMTA, and RAS models play complementary roles in wastewater treatment and internal water recycling on farms (Li et al., 2024).

Meanwhile, water quality monitoring and tailwater recycling systems require robust real-time monitoring support to operate efficiently and prevent system failures. Multi-sensor systems, Internet of Things (IoT) platforms, and artificial intelligence technologies can now continuously measure key parameters such as temperature, pH, dissolved oxygen, turbidity, conductivity, nutrients, and salinity, and provide early warning of critical events such as hypoxia, algal abnormalities, and sudden water quality changes. IoT-based RAS systems can also track water flow through biofilters, support assessment of biofilm formation, and enable remote automatic control of pumps and aeration equipment to maintain stable conditions under high stocking densities (Lindholm-Lehto, 2023; Tran-Minh, 2025). Therefore, integrating intelligent monitoring tools with ecological engineering units such as ecological ditches, constructed wetlands, purification ponds, and pond cascade systems can support adaptive management of water renewal, feed input, and treatment loading, promoting the transformation of ecological food chain closure from experience-based management to data-driven and intelligent management.

6 Major Problems in the Application of Ecological Food Chain Closure

6.1 System imbalance caused by unreasonable biological configuration

Ecological food chain closure emphasizes the coordinated configuration of different trophic levels and functional organisms, and its stable operation depends on rational species composition, stocking density, and trophic complementarity. However, in practical application, some aquaculture operators have insufficient understanding of pond ecosystem carrying capacity, biological niches, and interspecific relationships, and therefore tend to simply regard ecological closure as multi-species polyculture. If the proportions among the main cultured species, companion species, aquatic plants, and microorganisms lack a scientific basis, feeding competition, spatial competition, or functional overlap may occur among different organisms. For example, when filter-feeding fish are insufficiently configured, phytoplankton cannot be effectively regulated, making eutrophication more likely; when benthic animals are insufficient, deposited organic detritus cannot be utilized in a timely manner, increasing the risk of sediment deterioration; and when aquatic plants are excessively configured, water flow, nighttime dissolved oxygen levels, and the activity space of cultured animals may be affected. Relevant studies have also shown that inappropriate biological configuration may lead to interspecific competition, inefficient nutrient utilization, and environmental degradation.

In Mediterranean integrated multi-trophic aquaculture (IMTA) ponds, three fish species with different nominal trophic levels still mainly relied on commercial feed and competed for similar food sources, while macroalgae were barely utilized and only oysters effectively consumed excess phytoplankton. This indicates that, if feeding habits and natural productivity are not properly understood, the expected trophic complementarity may not be realized (Nahon et al., 2023). Studies on IMTA and biofloc technology have also pointed out that scientific species selection and appropriate population size are necessary conditions for achieving optimal biological and chemical processes; otherwise, ecosystem health and sustainability will be affected (Khanjani et al., 2022). In addition, unreasonable biological configuration may weaken the stability of ecological food chain closure. A closed-loop system does not mean that the more organisms of all types it contains, the better; instead, a dynamic balance among main production, resource utilization, and ecological regulation must be formed. If one trophic level is too strong or too weak, material cycling and energy transfer efficiency will both be affected.

Excessively high density of the main cultured fish increases feed input and metabolic waste discharge, making microbial decomposition and plant uptake capacity difficult to match. Insufficient aquatic plant coverage makes it difficult to perform nitrogen and phosphorus uptake and habitat stabilization functions. Improper supplementation of beneficial microorganisms may also fail to form dominant communities due to unsuitable water temperature, dissolved oxygen, or sediment conditions. Model analyses and field assessments indicate that misjudging pond carrying capacity and species functions may lead to system instability. An ecosystem model of crab-shrimp-clam ponds showed that system benefits peak near a specific stocking density; if stocking density continues to increase beyond this threshold, environmental standards may be exceeded and system performance may decline (Dong et al., 2023). Large-scale IMTA practices in Sanggou Bay also show that although complex species combinations have good ecological and production potential, they are difficult to manage because interspecific interactions are not yet fully understood, making unbalanced configurations likely. Therefore, species in ecological closed-loop systems should have ecological complementarity, local adaptability, and economic feasibility; otherwise, organic and inorganic loads will continue to accumulate, thereby weakening the realization of both environmental and economic objectives (Biswas et al., 2020; Knowler et al., 2020).

6.2 Effects of environmental changes on closed-loop operation efficiency

The operational efficiency of ecological food chain closure in freshwater ponds is significantly affected by environmental conditions. Factors such as water temperature, light, rainfall, dissolved oxygen, pH, water source quality, and sediment condition can all alter biological activities and material transformation processes within the system. Closed and semi-closed aquaculture systems are particularly sensitive to environmental changes because their self-purification processes, microbial transformations, and trophic interactions all depend on temperature, pH, and other external drivers. When water temperature is high, feeding activity of cultured animals increases and microbial decomposition accelerates, but the risk of declining dissolved oxygen also rises. When water temperature is low, the growth of aquatic plants and microbial activity weaken, and nutrient uptake and organic matter decomposition efficiency decline. Heavy rainfall, continuous cloudy and rainy weather, or hot and humid conditions may also cause water stratification, pH fluctuation, abnormal algal proliferation, or hypoxic floating, thereby affecting the normal operation of ecological closed-loop systems. Long-term dynamic simulations of ecosystem-based pond aquaculture indicate that climate change can simultaneously alter physical, chemical, and biological processes and affect carp growth and pond ecosystem functions over long time scales; therefore, environmental changes must be incorporated into pond planning and operational management (Varga et al., 2020). Comprehensive studies on the effects of temperature increase in aquaculture also indicate that anthropogenic warming can directly affect the growth, survival, reproduction, immunity, and microbiomes of cultured species, while indirectly increasing disease risk, parasite loads, and contaminant toxicity, thereby threatening the productivity of closed systems with limited buffering capacity.

Sediment conditions, water source quality, and changes in microbial networks are also important factors affecting closed-loop efficiency. Long-term high-density aquaculture ponds often experience sediment organic matter accumulation, anaerobic conditions in bottom layers, and release of harmful substances. Even if aquatic plants and beneficial microorganisms are introduced, poor sediment conditions may make it difficult to rapidly restore ecological functions. If the external water source contains high levels of suspended solids, nutrients, or pollutants, it will also increase the burden of pond ecological regulation. Environmental fluctuations can also reshape microbial networks and food-web structures, thereby affecting the stability of ecological closure. Long-term lake data show that seasonal changes in temperature and pH can alter microbial network complexity and keystone taxa; the loss or weakening of these keystone taxa can destabilize communities and reduce ecological stability. Studies on coastal fish communities have also found that an approximately 20% increase in temperature can lead to declining community diversity, a shift of interaction networks toward instability, and the emergence of critical slowing down, manifested as the dominance of a few competitive species and the reduction of cooperative species. In ecosystem-based ponds and IMTA systems, microorganisms and lower trophic organisms are important drivers of nutrient cycling. Therefore, community shifts caused by environmental changes may reduce nutrient removal efficiency, alter system carrying capacity, and increase the risks of regime shifts, eutrophication, and production losses when management measures fail to adapt. Thus, ecological food chain closure is not a fixed model that can operate stably independent of environmental conditions, but a dynamic system jointly influenced by seasonal changes, climate fluctuations, and pond baseline conditions (Varga et al., 2020).

6.3 Need for improvement in technical management and economic evaluation systems

Ecological food chain closure involves multiple links, including aquaculture species configuration, water quality monitoring, feed management, microbial regulation, aquatic plant management, tailwater treatment, disease prevention and control, and ecological benefit assessment. Therefore, it places higher requirements on the comprehensive management capacity of aquaculture operators. Compared with traditional pond aquaculture, ecological closed-loop aquaculture relies more heavily on process management and dynamic regulation and cannot be conducted through extensive experience-based operation alone. For example, feeding amounts need to be adjusted in a timely manner according to weather, water temperature, feeding behavior, and water quality indicators; aquatic plant coverage should be maintained at an appropriate level to avoid excessive growth or decomposition; and microbial agents should be applied based on dissolved oxygen, sediment condition, and organic load. If management is inadequate, ecological closed-loop models may not only fail to achieve expected results but may also increase production risks. Although ecological food chain closure and IMTA are considered to have the potential to improve sustainability and profitability, related studies indicate that current technical management systems remain insufficient. Reviews of IMTA economics show that there is still a lack of bioeconomic models and tools for comparing different systems and fully internalizing environmental externalities, and that economic incentive mechanisms and eco-certification frameworks require further improvement (Knowler et al., 2020). A comprehensive assessment of freshwater aquaculture in China found that its average ecological efficiency was only 0.702, indicating considerable room for improvement and clear regional differences. This suggests that current management has not yet fully coordinated production efficiency with environmental performance (Wang et al., 2024).

Meanwhile, the current economic evaluation system for ecological food chain closure aquaculture remains insufficient. Some practices place greater emphasis on water quality improvement, tailwater emission reduction, and ecological demonstration effects, while lacking systematic accounting of economic factors such as facility investment, labor costs, management costs, culture cycles, comprehensive output, product premiums, and long-term maintenance expenses. Economic evaluations of eco-friendly technologies and closed-loop systems remain fragmented. Systematic reviews of cost-benefit analysis in aquaculture show that, although related studies are increasing, environmental impacts and social costs are still insufficiently considered, and most studies have not yet incorporated ecological benefits into formal cost-benefit frameworks. Life cycle and economic analyses of aquaponics and aquaponics-IMTA systems also indicate that infrastructure, energy, and labor costs account for a relatively high proportion; for certain species or production scales, the benefit-cost ratio may be marginal or even negative, and profitability depends on the precise optimization of technical parameters, species selection, production scale, and market matching. Case studies of eco-friendly management show that such technologies have the potential to increase yield and reduce water and electricity use, but they also emphasize the need to establish standardized performance indicators, such as Aquaculture Performance Indicators, to simultaneously reflect environmental, economic, and social outcomes. For aquaculture operators, whether ecological models can be continuously promoted depends not only on whether their ecological benefits are evident, but also on whether their economic returns are stable. Therefore, in the future, a comprehensive evaluation system that integrates ecological, production, economic, and social benefits should be established to provide clearer decision-making support for pond aquaculture across different regions, species, and scales.

7 Countermeasures for Optimizing Ecological Food Chain Closure Aquaculture

7.1 Establishing a site-specific model selection mechanism

Optimizing ecological food chain closure aquaculture first requires establishing a site-specific model selection mechanism based on the natural conditions, aquaculture foundation, technical capacity, and industrial needs of different regions. Freshwater pond aquaculture is affected by multiple factors, including climate, water sources, sediment conditions, pond size, main cultured species, market positioning, and regional environmental carrying capacity. Therefore, the same ecological closed-loop model should not be simply applied across different regions. For example, in areas with good water sources, large pond areas, and a foundation for multi-species coordinated aquaculture, priority may be given to multi-trophic coordinated models such as fish-shrimp-shellfish-algae systems. In areas with high stocking densities and strong pressure from tailwater discharge, pond-ecological ditch-constructed wetland recycling purification systems are more suitable. In ponds with suitable conditions for aquatic plant cultivation or aquaponic development, fish-aquatic plant-microorganism ecological regulation models can be prioritized. Relevant studies have shown that spatial and habitat suitability models integrating hydrodynamics, water quality, and geomorphological characteristics can identify areas suitable for specific aquaculture types and reveal the feasibility and potential risks of models such as pond aquaculture, integrated multi-trophic aquaculture (IMTA), and shellfish culture in different regions (Falconer et al., 2016). Species distribution models and multi-criteria evaluation methods, such as Mahalanobis models, Maxent models, and multi-indicator suitability assessments, can also help planners screen models based on the characteristics of successful farms and optimal environmental thresholds, thereby reducing the negative impacts of inappropriate siting and spatial conflicts on sustainability.

In the process of model selection, ecological suitability, production feasibility, and economic rationality should be integrated. Aquaculture operators need to fully assess pond carrying capacity, baseline water quality, sediment conditions, tailwater discharge requirements, and the characteristics of the main cultured species before determining suitable biological configurations and facility construction plans. For small-scale farmers, low-input and easy-to-manage measures such as plant purification, microbial regulation, and moderate polyculture can be prioritized. For large-scale aquaculture bases, regional closed-loop systems can be constructed through ecological ditches, sedimentation ponds, constructed wetlands, recirculating aquaculture facilities, and digital monitoring platforms. At the farm and pond scale, ecosystem models and bioeconomic models can be used to simulate the effects of different stocking densities, species combinations, feed inputs, and tailwater treatment measures on aquaculture profits, nitrogen and phosphorus removal, and system stability, thereby providing quantitative support for site-specific integrated pond configurations (Biswas et al., 2020; Dong et al., 2023). Studies have also shown that integrated multi-trophic systems and recirculating systems generally outperform monoculture systems in terms of combined economic, ecological, and social benefits, providing an evidence base for local model selection and technical route formulation. Therefore, the selection of ecological food chain closure models should shift from experience-based judgment to an integrated decision-making process of "environmental suitability assessment-carrying capacity estimation-ecological-economic simulation-technical route matching."

7.2 Strengthening standardized technical systems and digital management

To achieve stable promotion of ecological food chain closure aquaculture, it is necessary to strengthen the development of standardized technical systems. At present, some ecological aquaculture practices still rely mainly on experience-based operation and lack unified standards in species matching ratios, stocking density, feeding management, aquatic plant coverage, microbial application frequency, tailwater treatment processes, and operational performance evaluation, resulting in unstable application outcomes. Therefore, operational, replicable, and evaluable technical standards should be established around key links such as pond renovation, biological configuration, feed management, water quality regulation, sediment remediation, tailwater purification, disease prevention and control, and product quality traceability. Standardized management can lower the implementation threshold of ecological closed-loop models and improve technical consistency and management comparability among different aquaculture operators. Relevant reviews have pointed out that standardized technical systems and digital tools are essential for the reliable operation of closed food-chain ponds under variable conditions. In the context of Industry 4.0, sensor networks, automated equipment, and decision-support tools can replace traditional manual and subjective monitoring, enabling real-time and evidence-based management of water quality, feeding, and system operation (Bernal-Higuita et al., 2023).

At the same time, the deep integration of digital technologies with ecological food chain closure aquaculture should be promoted. Freshwater pond ecosystems are characterized by dynamic changes, and relying solely on manual pond inspection and experience-based judgment makes it difficult to detect problems such as declining dissolved oxygen, rising ammonia nitrogen, abnormal algal communities, and sediment deterioration in a timely manner. By deploying online monitoring equipment for water temperature, pH, dissolved oxygen, ammonia nitrogen, nitrite, turbidity, conductivity, and other parameters, and combining these tools with intelligent aeration, remote warning, and data analysis platforms, continuous monitoring and precise regulation of pond environments can be achieved. IoT-based freshwater recirculating aquaculture systems (RAS) and pond systems can rely on physical, network, and logical architectures, using edge or fog computing devices, secure communication, databases, and intelligent analytics to monitor key variables such as dissolved oxygen and pH, and to drive actuators such as aerators, water pumps, and feeders for closed-loop control (Hala et al., 2024).

Advanced control methods can further improve management precision and system robustness. For example, fuzzy logic systems that integrate multiple sensors with cloud platforms can autonomously maintain appropriate dissolved oxygen, salinity, and pH levels and have demonstrated high accuracy and stability in real pond trials. Intelligent analytical methods, such as M5 model trees, random forests, and technologies for fish tracking, counting, and behavior analysis, can also improve the prediction of key water quality parameters, feeding regulation, and health warning, providing a foundation for unified monitoring standards and evaluation protocols (Bernal-Higuita et al., 2023). Therefore, the standardization of ecological food chain closure should be advanced together with digital platforms, incorporating best practices, monitoring indicators, and data models into technical guidelines for freshwater aquaculture to improve the stability and replicability of model promotion.

7.3 Constructing a coordinated evaluation system for ecological and economic benefits

The promotion of ecological food chain closure aquaculture should not emphasize ecological value alone; instead, a comprehensive evaluation system that integrates ecological, production, economic, and social benefits should be established. In terms of ecological benefits, priority should be given to evaluating water quality improvement, nitrogen and phosphorus reduction in tailwater, sediment remediation effects, reduced drug use, changes in greenhouse gas emissions, and resource utilization of aquaculture wastes. In terms of production benefits, attention should be paid to survival rate, growth rate, yield per unit area, feed utilization efficiency, disease incidence, and multispecies comprehensive output. In terms of economic benefits, facility investment, labor costs, energy costs, management costs, product prices, overall returns, and long-term maintenance expenses should be comprehensively calculated. In terms of social benefits, employment creation, food safety, green product supply, and the sustainable development of aquaculture communities should also be considered.

Ecological-economic evaluation studies have shown that, when ΔDPSIR, emergy analysis, and cost-benefit analysis are used to compare monoculture with IMTA, IMTA can simultaneously reduce nitrogen emissions, greenhouse gas emissions, and external resource harvesting, while moderately increasing farm profits. When public environmental benefits are monetized, total benefits are much higher than the increase in private profits (Knowler et al., 2020; Nobre et al., 2010). Comprehensive indicators such as emergy-based sustainability indices, environmental sustainability indices, and relative coefficients can also quantify trade-offs among resource use, environmental load, and economic returns, and identify better models among alternatives. In practical promotion, attention should also be paid to the value transformation of ecological products and the standardization of evaluation methods. Ecological food chain closure aquaculture can improve the culture environment, reduce dependence on pharmaceuticals, lower tailwater pollution, and enhance aquatic product quality. These advantages need to be transformed into economic returns through brand building, quality certification, green product labels, eco-labeling, and marketing.

For large-scale aquaculture bases, production records, water quality monitoring records, tailwater treatment records, and product traceability systems can be established to enhance product credibility and market recognition. For local specialty aquatic products, ecological aquaculture models can be combined with regional branding, recreational fisheries, and agricultural tourism to expand industrial value-added space. Broader reviews and meta-analyses have pointed out that current life cycle assessment of IMTA systems still faces methodological challenges, including the selection of functional units, data gaps, and inconsistent impact categories. Therefore, it is necessary to establish aquaculture-specific databases and unified life cycle assessment protocols to improve the comparability of different studies and aquaculture models (Hala et al., 2024). A global systematic review of shrimp farming models also shows that pond IMTA and recirculating systems perform better in terms of comprehensive, economic, ecological, and social benefits, but their results are sensitive to indicators such as survival rate, pH, and dissolved oxygen. This indicates that evaluation systems must incorporate both production process indicators and environmental process indicators. Therefore, evaluation of ecological food chain closure should integrate bioeconomic models, life cycle assessment, emergy analysis, cost-benefit analysis, and social indicators to provide a decision-making framework for measuring model performance, internalizing environmental externalities, designing policy incentives, and promoting the sustainable transformation of freshwater pond aquaculture (Nobre et al., 2010; Biswas et al., 2020; Knowler et al., 2020; Dong et al., 2023).

8 Conclusion and Prospects

Ecological food chain closure is based on the principles of material cycling and energy flow in ecosystems. Through the rational configuration of producers, consumers, and decomposers, feed, residual feed, feces, organic detritus, and dissolved nutrients generated during freshwater pond aquaculture can be transformed and reused across multiple levels within the system. Compared with traditional pond aquaculture models characterized by high input and high discharge, this model places greater emphasis on functional complementarity among organisms and the regulation of ecological processes. It can, to a certain extent, reduce the accumulation of aquaculture wastes, improve water quality and sediment conditions, and enhance resource utilization efficiency. Especially in the context of increasing requirements for green development and tailwater emission reduction in aquaculture, ecological food chain closure provides an important pathway for freshwater pond aquaculture to shift from a production-oriented model to an ecologically efficient model. Its value is reflected not only in yield improvement, but also in comprehensive benefits such as enhanced ecological stability, reduced disease risk, and lower environmental load.Ecological food chain closure aquaculture is not simply multi-species polyculture or the application of a single purification technology. Rather, it is a systematic engineering approach involving pond ecological structure design, aquaculture species configuration, water quality regulation, sediment remediation, tailwater recycling, and production management optimization. Therefore, in practical promotion, technical support, refined management, and market transformation need to be integrated. On the one hand, suitable ecological closed-loop models should be selected according to water source conditions, climatic characteristics, pond foundations, and main cultured species in different regions, and standardized operating procedures should be established to improve the stability and replicability of model application. On the other hand, training for aquaculture operators and the development of digital management should be strengthened. Online monitoring, intelligent aeration, precise feeding, and tailwater treatment facilities can be used to improve system operation efficiency. Meanwhile, attention should also be paid to transforming the market value of ecological aquaculture products. Green certification, brand building, and quality traceability can enhance consumer trust, allowing ecological benefits to be converted into sustained economic returns and thereby increasing the willingness of aquaculture operators to participate in ecological closed-loop construction.

In the future, freshwater pond aquaculture will further develop toward ecologicalization, intelligentization, standardization, and circularization. Ecologicalization emphasizes the construction of more stable multi-trophic structures in pond systems to enhance water self-purification and ecological regulation capacity. Intelligentization emphasizes the use of IoT sensors, data analysis platforms, and intelligent equipment to achieve precise management of water quality, feeding, aeration, and tailwater treatment processes. Standardization requires the formation of technical specifications and evaluation systems applicable to aquaculture scenarios involving different regions, species, and scales. Circularization emphasizes the reuse of aquaculture tailwater, nutrients, and biological resources, promoting the connection of pond aquaculture with crop production, wetland purification, and regional ecological governance. Overall, ecological food chain closure is not only an important technical pathway for the green transformation of freshwater pond aquaculture, but will also become an important support for modern aquaculture to achieve efficient resource utilization, environmentally friendly production, and sustainable industrial development.

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Conflict of Interest Disclosure

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