

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.