

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,