

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,