

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).