

Despite these advances, water quality dynamics remain a central scientific and management challenge in cage-cultured grouper. Marine cage farms discharge uneaten feed, feces, metabolites, and dissolved nutrients directly into surrounding waters, creating risks of eutrophication, oxygen depletion, and harmful shifts in plankton and microbial communities. Comparative studies between grouper cages and nearby non-aquaculture waters show significantly elevated dissolved inorganic nitrogen and soluble reactive phosphorus near cages, along with altered bacterial communities and strong correlations between microbial taxa and nutrient levels, highlighting eutrophication impacts of cage farming. Multi-parameter analyses in marine aquaculture areas further indicate that temperature, dissolved oxygen, salinity, inorganic nitrogen, chlorophyll a, and even antibiotic resistance genes are key drivers of temporal and spatial water quality variation, with cage systems strongly influenced by aquaculture activities and seasonality (Zhang et al., 2020).

Within cages, suboptimal water quality directly affects grouper physiology and health. For hybrid and cantang groupers, water quality factors such as ammonia and nitrite show strong correlations with cortisol levels, indicating that nitrogenous wastes act as major stressors in floating-net systems (Sulmartiwi et al., 2022). Experimental exposure to sub-lethal and acute concentrations of waterborne ammonia in juvenile hybrid groupers causes hematological disturbances, oxidative stress, altered antioxidant enzyme activities, and pronounced stress responses, including increased plasma cortisol and inflammatory and apoptosis gene expression, underscoring their sensitivity to nitrogen accumulation. Moreover, poor or imbalanced water quality can exacerbate disease outbreaks, as seen in humpback grouper cages where viral nervous necrosis is associated with stress and where temperature, dissolved oxygen, salinity, nitrate, and phosphate are critical parameters for maintaining health and preventing viral replication (Yanuhar et al., 2020).

Although many studies have identified sets of “critical” water quality parameters—typically including pH, dissolved oxygen, turbidity or suspended solids, and various forms of inorganic nitrogen—for cage systems in different regions, there is still no unified, species- and site-specific understanding of how these variables co-vary over time in grouper cages and how these dynamics translate into physiological stress, behavior changes, and production outcomes. Existing work in marine aquaculture areas has applied multivariate methods such as principal component analysis to identify dominant gradients and key drivers among temperature, salinity, dissolved oxygen, nutrients, organic matter, chlorophyll, and antibiotic resistance genes, suggesting powerful tools but leaving a gap in grouper-specific, cage-scale characterization of water quality change patterns. At the same time, technological solutions, including portable and automated multi-parameter monitoring devices, are being developed for grouper aquaculture to provide real-time data on temperature, pH, electrical conductivity, and dissolved oxygen, but practical implementation and integration with management decisions remain limited. Consequently, key scientific questions remain regarding the temporal and spatial patterns of water quality change within and around grouper cages, the relative importance of physical, chemical, and biological drivers, and the thresholds at which these changes translate into stress, disease susceptibility, and environmental degradation. Addressing these questions requires systematic monitoring and quantitative analysis of multi-parameter water quality data in operating grouper cage systems, coupled with an understanding of fish physiological responses and surrounding ecosystem processes. By focusing specifically on the characteristics of water quality changes in cage-cultured grouper, the present study aims to provide foundational evidence to guide water quality management, technological monitoring strategies, and eco-friendly farming practices for this economically important species group.

2 Overview of Grouper Cage Aquaculture Systems

2.1 Structure and types of cage farming systems

Modern marine fish farms mainly use open net cages supported by floating collars or platforms, typically circular plastic rings or steel structures that suspend large nets holding tens to hundreds of thousands of fish. These open systems contrast with closed containment tanks, and can themselves be classified into several structural types based on the nature of the supporting frame and containment method. Within open net systems, flexible floating ring cages are common nearshore, while larger rigid platforms and ship-shaped units are being developed for more exposed waters. Increasing interest in offshore and deep-sea cages has driven innovations combining rigid frames with flexible nets to withstand waves and currents and maintain cage volume for fish.