

7.2 Observed water quality dynamics

Comparisons between grouper cages and nearby reference waters revealed pronounced differences in nutrient status and eutrophication indicators. Dissolved inorganic nitrogen and soluble reactive phosphorus were significantly higher in aquaculture waters, indicating enhanced nutrient loading associated with feed inputs and metabolic wastes (Liu et al., 2024). These nutrient enrichments occurred despite the relatively small vertical extent of the cages, suggesting that even shallow water columns can accumulate substantial dissolved nutrients when flushing is limited.

Patterns observed in this grouper system are consistent with broader analyses of marine cage aquaculture areas. In a northern China marine farming region, multiseason sampling at 19 sites showed that chlorophyll a, salinity, dissolved oxygen and inorganic nitrogen dominated principal components for cage areas, with the heaviest pollution occurring in November when aquaculture activity and seasonal conditions combined to elevate scores. These results indicate that nutrient enrichment and oxygen dynamics in cage systems show both spatial contrasts with nearby non-aquaculture zones and marked temporal variability linked to farming operations and seasonality.

7.3 Relationship between aquaculture activities and environmental responses

The grouper case study demonstrates clear coupling between aquaculture practices and environmental responses. Elevated nutrients and eutrophication indicators in cages relative to adjacent waters coincide with significant shifts in planktonic bacterial communities, including increased abundances of *Vibrio* and *Pseudoalteromonas* and altered functional genes for carbon, nitrogen and sulfur metabolism. Correlation analyses show that many taxa respond positively to dissolved inorganic nitrogen and soluble reactive phosphorus but negatively to dissolved oxygen, indicating that nutrient enrichment and oxygen stress jointly structure microbial assemblages in grouper cages.

Similar linkages between aquaculture pressure and water quality emerge at larger spatial and temporal scales. In the Zhuanghe marine aquaculture region, principal component analysis integrating pH, temperature, salinity, dissolved oxygen, nutrients, chlorophyll a, chemical oxygen demand and antibiotic resistance genes identified aquaculture activities and seasonality as the main drivers of water quality in cage areas (Zhang et al., 2020). Moreover, cage areas showed higher variety and frequency of antibiotic resistance genes than pond systems, suggesting additional environmental stressors linked to terrestrial inputs and farm management. Together, these findings highlight that feed inputs, stocking practices, and ancillary inputs in grouper cage aquaculture not only alter classical physicochemical indicators but also drive complex microbial and genetic responses in the surrounding environment.

8 Impacts of Water Quality Changes on Grouper Health and Growth

8.1 Stress responses and physiological metabolism changes

Water quality directly shapes stress status and metabolic regulation in grouper, with several studies highlighting specific pathways. Elevated unionized ammonia causes hematological depression, oxidative stress, and increased stress indicators such as plasma cholesterol and heat shock protein 70 in juvenile hybrid grouper, demonstrating systemic physiological disruption under poor water quality. Combined hypoxia and ammonia exposure further elevates oxygen consumption and activates genes involved in glucose and amino acid metabolism, indicating that co-occurring stressors substantially increase energetic costs to maintain homeostasis (Cao et al., 2024).

Other water-quality-related stressors, particularly temperature fluctuation, alter metabolic profiles at molecular and organismal levels. Mucus and serum metabolomics under temperature fluctuation stress identified disturbances in purine metabolism, TCA cycle, and methionine and pyruvate metabolism in juvenile hybrid grouper, differentiating susceptible from resilient phenotypes. Elevated temperature (33 °C-36 °C) over 14 days significantly reduced body weight, suppressed antioxidant enzymes, and altered digestive enzyme activities, with high-temperature exposure classified as a high-stress level by a quantitative hazard system.

8.2 Disease occurrence and links to water quality

Suboptimal water quality can aggravate disease outcomes, even when basic parameters remain within nominal ranges. In humpback grouper cages infected by viral nervous necrosis (VNN), measured temperature, pH, dissolved oxygen, salinity, nitrate, and phosphate stayed within values considered normal for the species, yet fish showed