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Characteristics of Water Quality Changes in Cage-Cultured Grouper

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Abstract This study investigates the water quality dynamics in grouper (*Epinephelus* spp.) cage aquaculture systems, with a focus on identifying spatiotemporal variation patterns, driving mechanisms, and their ecological implications. Based on field monitoring and systematic analysis, key water quality parameters-including temperature, salinity, dissolved oxygen, pH, nutrients, and organic matter-were evaluated to characterize environmental variability within and around cage farming areas. The results indicate that water quality exhibits pronounced diurnal, seasonal, and spatial heterogeneity, primarily driven by tidal exchange, hydrodynamic conditions, and meteorological forcing. Aquaculture activities, particularly feed input and metabolic waste release, significantly contribute to nutrient enrichment and organic load accumulation, which may further alter microbial community structure and ecosystem stability. External environmental factors, such as rainfall events, wind-driven mixing, and adjacent coastal pollution inputs, also play important roles in modulating water quality fluctuations. A case study from a representative aquaculture region further demonstrates the interaction between farming intensity and environmental response. Finally, the study discusses the impacts of deteriorating water quality on grouper physiological stress, disease susceptibility, and growth performance, and proposes integrated management strategies including ecological carrying capacity control, real-time monitoring systems, and sustainable aquaculture practices. These findings provide scientific support for optimizing cage aquaculture management and improving coastal water environmental sustainability.
Keywords Grouper aquaculture; Cage culture; Water quality dynamics; Spatiotemporal variation; Environmental management

1 Introduction

Grouper cage aquaculture has expanded rapidly in tropical and subtropical coastal waters and is now a major marine fish farming sector in Asia, supplying high-value protein and income for coastal communities. This growth coincides with broader global expansion of marine cage culture, where waste discharge, nutrient loading, and associated changes in water quality are recognized as key limiting factors for sustainable development (Zhang et al., 2020). Water quality shapes fish physiology, behavior, health, and welfare; changes in temperature, turbidity, dissolved oxygen, salinity, pH, inorganic nitrogen, and emerging pollutants can produce profound effects on metabolism, organs, and behavior that ultimately determine growth and survival in culture systems (Zhang et al., 2024). Against this backdrop, clarifying the characteristics of water quality changes in cage-cultured grouper has both scientific and practical significance for optimizing production, safeguarding fish welfare, and protecting surrounding coastal ecosystems.

Grouper production now involves at least dozens of species and hybrids, with Asia dominating global output and many small-scale farmers depending on this activity for employment and income. Hybrid groupers, such as crosses between tiger grouper (*Epinephelus* fuscoguttatus) and giant grouper (*E. lanceolatus*), have been widely adopted because of high growth potential, production efficiency, and resilience, supporting commercial-scale farming across the Asia-Pacific region. Grouper culture is now recognized as one of the highest-yielding marine aquaculture sectors in China, where hypoxia and other environmental stresses associated with intensified production, elevated temperatures, and high-density transport have become major constraints (Wang et al., 2026). At the same time, eco-friendly aquaculture management technologies are being promoted to increase grouper output per unit area while reducing water and energy use, showing that management innovations can enhance both economic returns and resource efficiency (Cheng et al., 2024).

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.

2.2 Environmental characteristics of farming areas

Site hydrodynamics strongly influence suitability for cage farming and water quality around cages. In Kenyan coastal sites, temperature ranged roughly 26°C-33 °C, with deeper, higher-tidal areas showing cooler water and greater column depth, while current speeds and wave heights varied widely between mangrove creeks and open channels (Mirera et al., 2023). These differences mean cage designs and deployment must be tailored to local depth, currents, waves, and shelter conditions. Cage arrays themselves modify surrounding hydrodynamics by adding drag and reducing current speed, which can slow pollutant transport and water exchange. Numerical modeling in the North Yellow Sea showed velocity inside dense cage areas could fall by up to about 45%, creating low-flow zones where solute transport is inhibited and food supply from surrounding waters is reduced (Jiang et al., 2022).

2.3 Stocking density and management practices

Stocking density is a key management lever because it directly shapes growth, feed conversion, survival, and water quality. A review of intensive systems found that excessive densities reduced specific growth rate by 8%-42%, increased feed conversion ratio by 10%-35%, and lowered survival by 5%-28% compared with optimal levels (Firayani, 2024). These biological effects were closely linked to declines in dissolved oxygen and rises in total ammonia nitrogen as biomass and waste loading increased. Field studies in cage farms similarly show that moderate densities often balance yield with fish health and environmental stress. In Lake Victoria cages, densities within a recommended range of 70-150 fish • m^{-3} achieved better growth and health outcomes, whereas sub-optimal higher or lower densities were associated with reduced yields and more frequent fish kills in areas prone to poor water quality (Aura et al., 2025). Similar patterns are reported for other cage-reared species, where lower densities often produce higher individual growth and better survival, underscoring the need to align biomass with the assimilative capacity of the farming site.

3 Key Water Quality Indicator System in Cage Aquaculture

3.1 Physicochemical parameters

Temperature, salinity, dissolved oxygen (DO), and pH form the core physicochemical indicators in cage aquaculture because they directly affect fish metabolism, growth, and survival. Temperature and DO jointly characterize growth conditions, and multivariate analyses in marine aquaculture areas consistently identify them as critical factors for cultured organisms. In a review of fish responses to these variables, shifts in any of these four parameters are described as having strong impacts on physiology, behavior, and population dynamics, emphasizing their role as primary management targets (Mariu et al., 2023).

Field measurements in marine cage and pond systems show that pH typically varies in a narrow range near neutrality or slight alkalinity, while temperature, salinity, and DO exhibit stronger temporal and spatial fluctuations that structure water quality patterns (Zhang et al., 2020). Detailed profiling in commercial sea-cages further reveals substantial three-dimensional variability in temperature and DO within a single cage, with DO occasionally dropping to levels known to limit feed intake and growth, underscoring the need for fine-scale monitoring of these physicochemical indicators.

3.2 Nutrients and organic pollutants

Nitrogen, phosphorus, and organic carbon are key indicators of nutrient loading and organic pollution from cage aquaculture, as uneaten feed and feces are major external inputs. A global review of cage systems estimated that for each ton of fish produced, more than 130 kg of nitrogen and 25 kg of phosphorus can be released to the environment, highlighting cages as important nutrient sources to coastal waters. Mass-balance modeling at bay scale similarly quantified annual releases of over 200 tons of nitrogen and nearly 40 tons of phosphorus from marine cages, confirming that dissolved inorganic forms dominate the nutrient load and can alter ambient nutrient ratios (Figure 1).

Increased nitrogen, phosphorus, and organic matter not only affect the water column but also accumulate in sediments beneath long-term farming areas. Core profiles from semi-enclosed bays show that total nitrogen, total phosphorus, and total organic carbon in surface sediments often exceed safety thresholds, with moderate to severe pollution linked to prolonged cage farming and low current speed (Cai et al., 2023). Comparative surveys around grouper cages further demonstrate significantly elevated dissolved inorganic nitrogen and soluble reactive phosphorus relative to non-aquaculture waters, identifying these nutrient indicators as central to assessing eutrophication pressure in cage-culture zones (Liu et al., 2024).

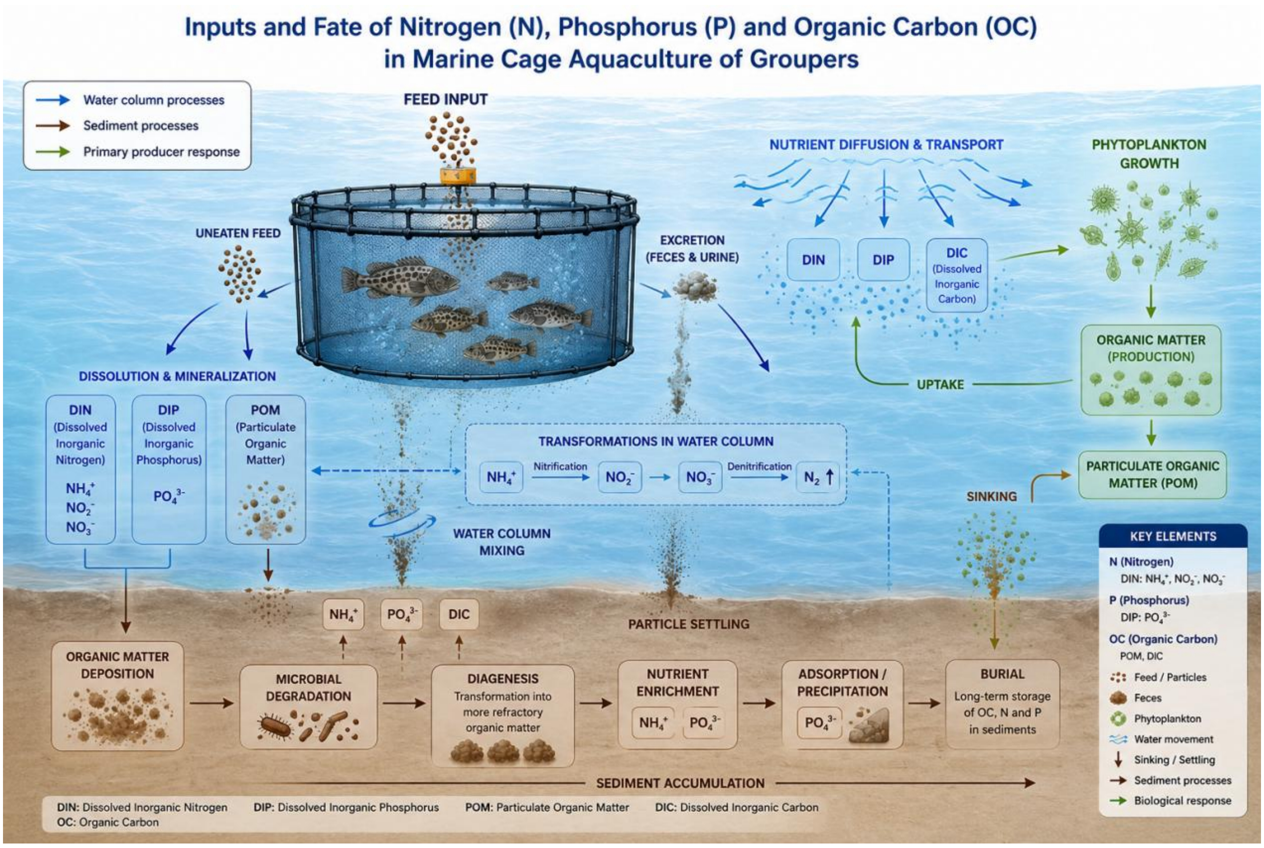

Figure 1 Conceptual pathways of nitrogen, phosphorus, and organic carbon release from grouper cage aquaculture and their transport into the surrounding water column and sediments

Note: Uneaten feed and fish feces are the primary sources of nutrient inputs in cage aquaculture. Released dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), and particulate organic matter (POM) contribute to eutrophication and organic enrichment of sediments

3.3 Biological indicators and microbial community characteristics

Biological indicators, especially microbial communities, provide sensitive and integrative measures of water quality changes in cage aquaculture environments. Comparative metagenomic analysis between grouper cages and nearby non-farmed waters has shown that bacterial diversity and functional genes related to carbon, nitrogen, and sulfur metabolism are significantly altered where eutrophication indicators are elevated (Liu et al., 2024). Correlation analyses indicate that many microbial taxa increase with dissolved inorganic nitrogen and soluble reactive phosphorus but decrease with DO, linking microbial assemblages directly to physicochemical and nutrient indicators.

Beyond planktonic bacteria, broader microbiome-based approaches emphasize microorganisms as both indicators and managers of water quality. Conceptual frameworks propose using shifts in microbial nitrogen and phosphorus transport and metabolism, together with community composition, as early-warning signals of self-pollution and environmental impact in aquaculture systems. Field studies in marine reservoirs with net-cage culture report elevated total heterotrophic bacteria and more frequent detection of fecal indicators such as Escherichia coli at cage sites compared with reference locations, illustrating how microbial counts and specific taxa can serve as practical biological indicators of organic loading and contamination in cage-culture waters.

4 Spatiotemporal Variability of Water Quality

4.1 Diurnal variation and tidal forcing mechanisms

Within cage farms, dissolved oxygen (DO) and related parameters often fluctuate markedly over the day-night cycle. Continuous monitoring in seabass cages showed that DO saturation inside cages could be 10%-50% lower than outside, with hypoxic conditions (40%-70% saturation) occurring frequently during summer and autumn. These diurnal patterns were closely linked to fish feeding activity and daily rhythms of plankton, with minimum DO typically coinciding with feeding periods and high temperatures rather than with peak daytime photosynthesis. Tidal currents further modulate short-term DO variability at farm scale. At a commercial salmon farm, tide was the dominant driver of DO levels, producing pronounced differences between up-current and down-current cages during each tidal phase (Burke et al., 2020). As water flowed across the farm, fish respiration and flow restriction acted cumulatively so that downstream cages exhibited substantially lower DO than upstream locations at any given time.

Computational studies show that changes in tidal regime can dramatically alter the duration and volume of low-oxygen water within cage structures. When maximum current speed was halved, or slack tide and tidal cycle length increased, the time that large cage volumes experienced lethal DO levels (<30% of ambient) increased from near zero to more than an hour (Nguyen et al., 2025). These findings highlight the interaction between fish density, current speed, and tidal characteristics in controlling diurnal DO risk and emphasize the need to adjust stocking density to local tidal dynamics.

4.2 Seasonal variation patterns

Seasonal forcing generates strong temporal patterns in cage-area water quality, often through changes in temperature, stratification, and primary productivity. In a seabream cage farm off Oman, summer surface temperatures reached ~32 °C and extended hypoxia developed below 35 m, whereas winter conditions were more vertically homogeneous and less extreme. Short up- or down-welling events driven by energetic flow pulses broke stratification and caused rapid shifts in temperature and oxygen, underscoring the importance of seasonal mixing dynamics for farm management (Al-Yahyai et al., 2020). Multivariate analyses of marine aquaculture areas in northern China also demonstrate pronounced seasonal changes in water quality. In a cage culture area, principal component scores indicated that overall pollution burden peaked in November, when declining temperature, reduced primary productivity, and intensive harvest activities coincided to elevate key indicators.

In contrast, summer conditions with strong light and suitable temperatures favored phytoplankton growth and nutrient drawdown, leading to relatively lower nutrient concentrations despite high biological activity (Zhang et al., 2020). In inland and reservoir cage systems, seasonality similarly shapes key limnological variables. In a large Brazilian reservoir, PCA of a multi-year dataset around a great-volume cage system revealed two phases: a pre-farming period characterized by higher DO and temperatures, and a post-production period marked by elevated ammonium and total phosphorus, with these shifts strongly influenced by seasonal hydrology (Rosini et al., 2019). Seasonal rainfall further reduced transparency by transporting allochthonous material and suspended solids, decoupling clarity from phytoplankton abundance.

4.3 Spatial heterogeneity and distribution characteristics

At the scale of individual farms, water quality often varies between cage and reference sites as well as along flow paths. In a tropical marine cage farm, nutrient concentrations and chlorophyll a were generally higher than in pristine environments, but temperature, salinity, DO, and pH did not differ significantly between stations near and away from cages over a year. This pattern suggests that high organic loading can elevate nutrients and bacterial abundance without always producing strong horizontal gradients in basic physico-chemical parameters. Other systems show clearer horizontal gradients related to farm location and broader limnological context. In Lake Victoria, water transparency increased and nutrient loading decreased with distance from eutrophic inner gulf sites toward more oligotrophic open-lake areas, forming a strong regional gradient that overshadowed local cage-control differences (Okechi et al., 2022). Despite higher fish biomass near cages, principal component scores for eutrophication and seasonal variability did not differ significantly between paired cage and control stations at any site.

Spatial comparisons across multiple mariculture systems reveal that system type and layout also influence water quality patterns. In a Chinese coastal region containing seaweed, shellfish, and cage-fish areas, DO and transparency were relatively higher in seaweed zones, while nutrient concentrations were elevated in cage fish and shellfish areas compared with a blank control, indicating distinct local water quality signatures for each system (Zhu et al., 2023). Principal component and redundancy analyses further linked spatial differences in phytoplankton composition to gradients in total nitrogen, salinity, and transparency, illustrating how physical and chemical heterogeneity structures biological communities within and among farming areas.

5 Mechanisms of Aquaculture Activities Affecting Water Quality

5.1 Feed input and residual feed decomposition processes

In cage-culture systems, feed is the primary input of nutrients and organic matter, and a considerable fraction is not converted into fish biomass but lost as uneaten pellets and associated particulates. Mass-balance analyses show that only about 39%-43% of feed nitrogen and phosphorus are retained in salmon tissues, with the remainder released as organic particulates and dissolved wastes (Wang and Olsen, 2023). Conceptual nutrient budgets for cage aquaculture similarly indicate that on the order of 130 kg •N and 25 kg •P can be discharged per ton of fish produced, emphasizing the central role of feed inefficiency in nutrient emissions.

Uneaten feed that sinks below cages undergoes mineralization, releasing dissolved inorganic nitrogen and phosphorus and contributing to eutrophication, oxygen depletion, and increased biological oxygen demand. Studies in floating net cages report that 20%-30% of feed is uneaten and partially decomposes in the water, becoming a major source of nitrogen, phosphorus, and organic matter pollution (Astuti et al., 2023). Reviews of aqua-feed wastes further note that the dietary composition of feeds governs the proportion and form of nitrogenous and phosphorus compounds entering the environment, which in turn drive changes in pH, algal turbidity, and eutrophication risk.

5.2 Waste excretion and organic load accumulation

Beyond uneaten feed, fish metabolism generates substantial dissolved and particulate wastes that accumulate in and around cages. Mass-balance models for Atlantic salmon indicate that approximately 18% of consumed carbon, nitrogen, and phosphorus is lost as defecation, while 39%-43% is released through excretion or respiration, underscoring the importance of metabolic pathways in waste generation. Similar modeling approaches for cage farms estimate that over 60% of phosphorus waste is solid, whereas more than 65% of nitrogen waste is excreted as dissolved ammonia, illustrating how excretion loads the water column with reactive nitrogen.

These waste fluxes can alter water and sediment chemistry when they exceed local assimilative capacity. In a eutrophic lake with Nile tilapia cages, increased concentrations of nitrogen and phosphorus near cages stimulated algal growth, while organic material accumulated beneath cages elevated benthic biochemical oxygen demand and promoted anoxic conditions and reduced redox potential (Musa et al., 2022). A broader review of aquaculture wastewater confirms that aquafeed, drugs, and metabolic wastes collectively contribute conventional pollutants and organic compounds to receiving waters, requiring improved treatment and management to avoid long-term environmental and health risks (Liu et al., 2024).

5.3 Biological disturbance and ecological feedback effects

Organic enrichment from feed and wastes modifies benthic habitats, driving biological disturbance and feedbacks on water quality. Case studies around Mediterranean fish farms show that sediments beneath cages experience biodiversity loss and are dominated by opportunistic species such as *Capitella* sp. I, with the impact generally confined to tens of meters but closely linked to cultured biomass and hydrodynamic conditions. Similar patterns appear in tropical environments, where elevated organic waste deposition directly beneath and adjacent to cages leads to highly perturbed macrobenthic communities with extremely low diversity and dominance of second-order opportunists (Grouazel et al., 2025).

Bioturbation and bioirrigation by benthic fauna can partially moderate these impacts, but also alter ecosystem functioning near farms. Work at the edge of an allowable zone of effect found that higher bioturbation potential near cages reshaped microphytobenthic communities and trophic structure, shifting dominance toward euglenophytes and scavenging macrofauna while still supporting diverse trait combinations. Long-term observations of meiofaunal recovery after farm removal indicate that, although densities may begin to rebound within months, community structure and taxa richness remain altered, revealing time-lagged ecological feedbacks between past organic loading, benthic communities, and subsequent ecosystem resilience.

6 External Environmental Drivers of Water Quality Dynamics

6.1 Ocean hydrodynamic exchange processes

Ocean hydrodynamics govern how wastes and nutrients from cage-cultured grouper are diluted, transported, or retained around farms. Numerical simulations in the North Yellow Sea showed that suspended cages create low-velocity zones inside farm areas, with current speed reduced by up to about 45% under high-density culture, which in turn inhibits pollutant transport away from cages (Jiang et al., 2022). Similar modeling work in Sansha Bay found that near-surface current speed in cage-free areas was more than three times that inside cage areas in deep channels, indicating strong cage-induced drag that can slow horizontal water exchange.

Three-dimensional hydrodynamic studies further show that cages modify both horizontal and vertical flow structures, affecting the dispersion of dissolved and particulate effluents. High-resolution modelling demonstrated complex perturbations to tidal flows around cage arrays and revealed that altered currents strongly influence redistribution of passive tracers such as feed, faeces, or dissolved markers through and within cages. Observations in a semi-enclosed bay similarly identified a "double-drag" structure, with cage-induced surface friction reducing current velocities by up to 54% and hindering horizontal water exchange, while enhanced shear and turbulence below cages locally improved vertical mixing (Figure 2) (Jiang et al., 2022).

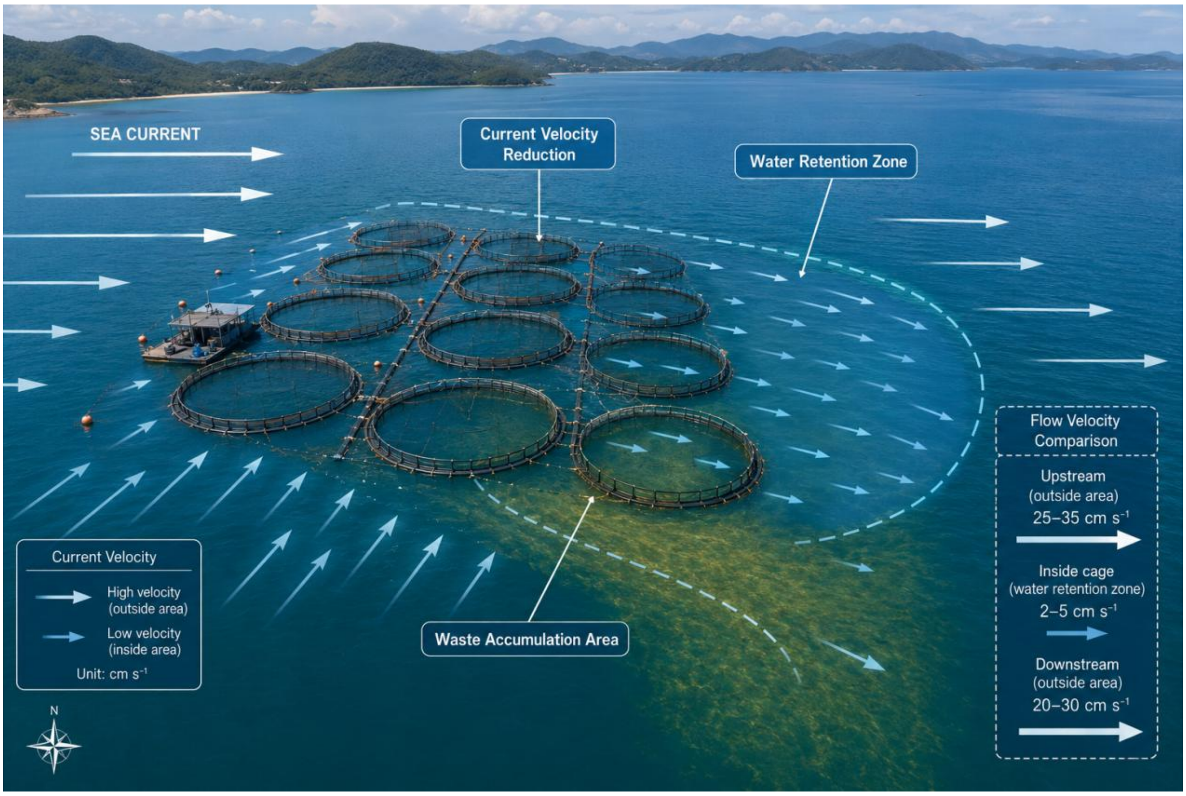

Figure 2 Hydrodynamic interaction between grouper cage arrays and surrounding coastal waters

Note: Cage structures obstruct water movement and create low-velocity zones within farming areas. Reduced current speeds increase water retention and may promote local accumulation of nutrients and organic wastes

6.2 Meteorological influences

Meteorological forcing alters stratification, circulation, and external inputs, thereby reshaping water quality around cage farms. Remote-sensing analysis of Typhoon In-fa in the Zhoushan fishery showed that strong vertical mixing from the typhoon led to a marked decrease in sea surface temperature, with more intense cooling on the right side of the track due to asymmetric wind stress and pre-existing temperature structure (Tang et al., 2023). Despite mixing and inflow of hypersaline water, intense rainfall and diluted water input caused an overall post-typhoon decrease in sea surface salinity, illustrating how wind and rain jointly modify the hydrographic context in which cages operate.

Typhoons also directly affect wave and current regimes, with implications for cage integrity and water exchange. Simulation of typhoon Rammasun in Maniao Bay predicted that during the storm, significant wave height in the cage area exceeded 5.5 m and maximum flow velocity reached about 1.5 m • s^{-1}, surpassing the design carrying capacity of deep-water cages and leading to potential deformation or damage (Zhang et al., 2024). Broader reviews of mariculture net-cage disasters in China emphasize that strong winds and waves associated with typhoons can cause overtopping, frame collapse, and structural instability, producing abrupt changes in the rearing environment that depress growth and increase disease and escape risk.

6.3 Pollution inputs from surrounding marine areas

External pollution inputs from the wider marine environment interact with farm-derived wastes to shape water quality in cage-culture zones. An evaluation of marine aquaculture areas using principal component analysis showed that in cage regions, chlorophyll a, salinity, and dissolved oxygen were dominant factors, while antibiotic resistance genes (ARGs) appeared more diverse and frequent in cages than ponds, suggesting terrestrial inputs contribute to pollution signatures beyond farm discharges alone. In Lake Victoria, comparisons along a strong background eutrophication gradient indicated that terrestrial and other non-cage sources were the major drivers of gulf-wide nutrient enrichment, with cage farms showing no significantly higher nutrient enrichment or turbidity than ambient conditions at paired control sites (Okechi et al., 2022).

At the same time, cumulative nutrient outputs from multiple farms can contribute substantially to regional nutrient budgets and interact with external sources. A global synthesis estimated that each ton of fish produced in marine cages releases on the order of 132.5 kg • Nitrogen and 25 kg • Phosphorus, raising concern that additive discharges from many farms, together with other coastal inputs, may enhance primary production and eutrophication in intensively farmed regions. Long-term analysis in Sansha Bay quantified large percentage increases in sediment heavy metals and substantial enhancements of dissolved inorganic nitrogen and phosphorus attributable to cage culture compared with conservative mixing, demonstrating how aquaculture activities amplify contamination on top of natural and external background processes in semi-enclosed coastal systems (Song et al., 2023).

7 Case Study: Water Quality Dynamics in a Typical Grouper Cage Aquaculture Area

7.1 Study area description and monitoring design

A representative example of grouper cage aquaculture is found in Xincun Port, Lingshui County (Hainan, China), where fixed marine cages dominate the sheltered inner bay. All sampling sites in the aquaculture area are fixed cages with the net body extending 0.7-1.0 m above the surface and 1.5-2.5 m below, stocked exclusively with giant grouper (*Epinephelus lanceolatus*). The farming zone is embedded within a semi-enclosed port that also contains nearby non-aquaculture waters, providing a natural reference for assessing aquaculture impacts under similar hydrological conditions (Liu et al., 2024).

Water quality monitoring in this case followed an integrated design combining in situ profiling and laboratory analyses. Surface water (~1 m depth) was sampled once in May from three aquaculture cages and three non-aquaculture sites, with temperature, dissolved oxygen, conductivity, salinity, redox potential and pH measured immediately using a handheld multiparameter meter. Bulk water was then filtered for colorimetric determination of ammonium, nitrite, nitrate and soluble reactive phosphorus, allowing calculation of dissolved inorganic nitrogen and construction of a multi-indicator dataset linking physicochemical conditions to microbial communities.

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 severe clinical signs and high mortality, indicating that poor water quality mainly increases stress and susceptibility rather than acting as the sole cause of infection. A broader systematic review of marine cage culture in East and Southeast Asia notes that environmental triggers, including water quality deterioration, are important in initiating outbreaks of Vibrio spp., parasitic infections, and viral diseases such as iridoviruses and nervous necrosis virus (Jahangiri et al., 2022).

Quantitative farm-level data link specific water quality variables to pathogen presence in cage-cultured grouper. A survey of marine cages found multiple co-occurring pathogens, including Vibrio alginolyticus, V. vulnificus, Photobacterium damselae, nervous necrosis virus, and iridovirus, and identified water temperature, dissolved oxygen, ammonia, iron, and nitrite as the most significant physicochemical factors associated with their occurrence. A review of fish health aspects in grouper culture further emphasizes that environmental deterioration and intensive practices contribute to frequent viral, bacterial, and parasitic disease problems, complicating large-scale production (Figure 3).

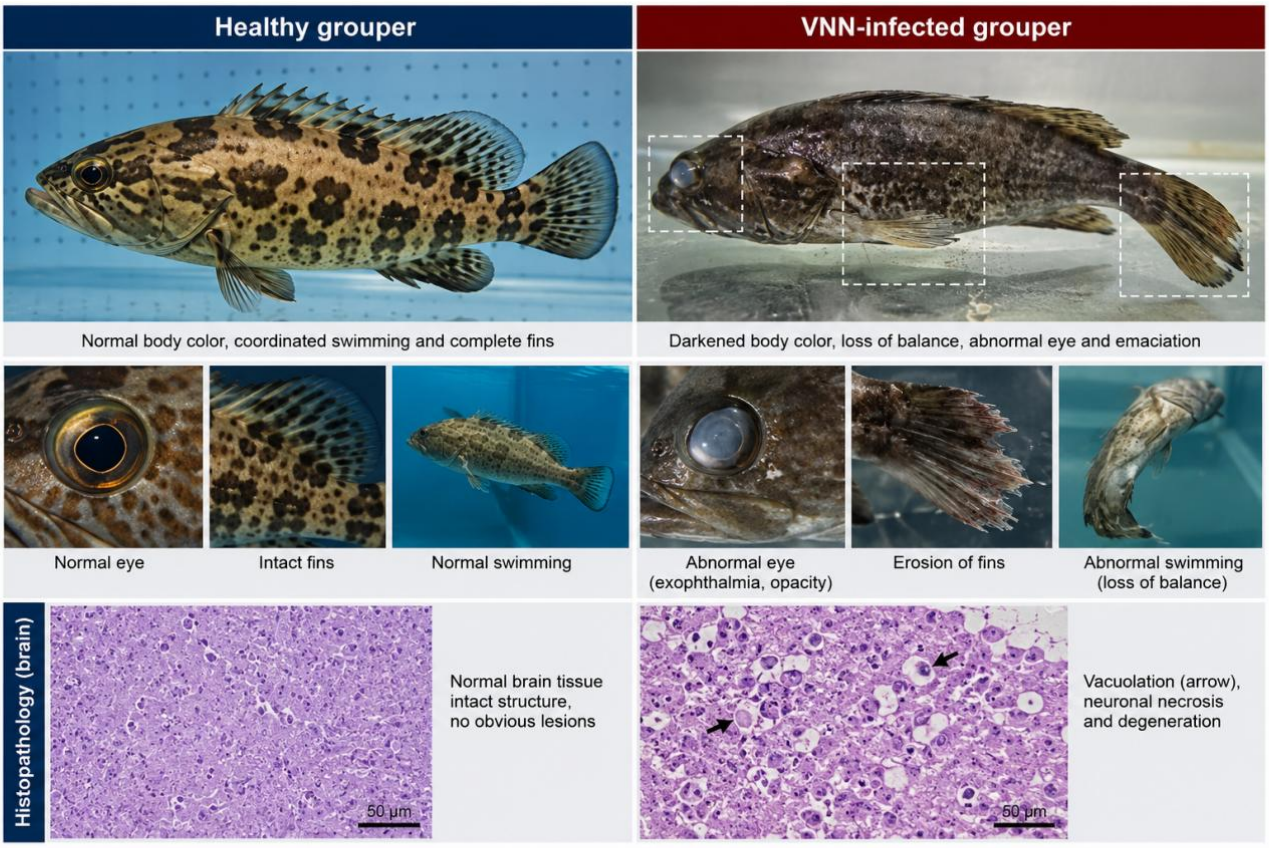

Figure 3 Representative clinical signs observed in healthy and diseased cage-cultured grouper

8.3 Growth performance and survival rate variations

Water quality management regimes strongly influence grouper growth and survival outcomes. In a 40-day nursery trial comparing flow-through, recirculation, and recirculation with bioremediation, the bioremediation treatment achieved the most stable salinity and ammonia ranges and inhibited Vibrio spp., yielding the highest survival (94.8 %), fastest length and weight growth, and lowest feed conversion ratio (Ismi et al., 2023). Similarly, combining water exchange with siphoning in hybrid grouper culture improved water quality by reducing ammonia, phosphate, and total organic matter, and achieved 100 % survival and better feed utilization than treatments with poorer waste removal (Putra et al., 2025).

Specific water quality parameters also determine growth efficiency and mortality risk. Cage experiments with tiger grouper under different salinities showed that 32 psu produced the highest absolute and specific growth rates and survival, along with the most favorable feed conversion ratio, whereas lower salinities reduced survival. In multitrophic microcosms, brown-marbled grouper survival (47%-87%) was lower than previous reports despite generally acceptable temperature, salinity, and pH, and high ammonia and phosphate concentrations were identified as likely causes of the reduced survival, highlighting the lethal impact of nutrient accumulation even when other parameters appear adequate. Water quality regulation is central to sustaining cage-cultured grouper, as intensive feeding, high stocking densities, and constrained hydrodynamics can rapidly drive eutrophication, oxygen depletion, and disease. This section outlines strategies that align ecological carrying capacity, real-time control, and green technologies to maintain stable water conditions while supporting viable production.

9 Water Quality Regulation and Management Optimization Strategies

Ecological regulation in cage-cultured grouper begins with matching farming intensity to the assimilative capacity of surrounding waters. Studies on cage aquaculture show that exceeding environmental carrying capacity leads to nutrient accumulation, algal blooms, and benthic degradation, directly undermining fish health and long-term productivity. Carrying capacity can be estimated using mass-balance or Bayesian models that link allowable biomass to key indicators such as chlorophyll-a, particulate nitrogen, and hydrodynamics. In practice, this translates into limits on total biomass, cage number, and stocking density per farming zone, combined with strict control of feed inputs and phosphorus content to restrain eutrophication. Spatial planning is equally important for grouper cages. Hydrodynamic-based site selection favors areas with sufficient depth and current speeds that disperse wastes without exporting impacts to sensitive habitats or conflicting water users. Zoning and registration systems that concentrate cages in designated areas, cap total units, and remove illegal or excessive structures help keep production within ecological limits and reduce conflicts over water use. Within farms, better management practices-optimized stocking density, phased fallowing, and selective adoption of semi-intensive over highly intensive feeding regimes-can maintain acceptable dissolved oxygen, ammonia, and organic loading while sustaining economic returns. Community-based governance frameworks further support compliance and adaptive adjustment of carrying capacity thresholds as environmental conditions change.

Real-time monitoring systems have become indispensable for managing water quality dynamics around grouper cages. Sensor-based platforms using microcontrollers, wireless communication, and low-cost probes can continuously track temperature, dissolved oxygen, pH, turbidity, and salinity at relevant depths. Unlike manual sampling, these systems provide high-frequency data, allowing early detection of hypoxia, acidification, or turbidity spikes linked to storms, floods, or operational failures. Calibration against reference instruments and protective sensor housings improve accuracy and durability, making such systems suitable for prolonged deployment in coastal and offshore environments. Early warning functions transform raw monitoring data into actionable management responses. Threshold-based alerts delivered via SMS, mobile apps, or IoT dashboards notify farmers when parameters deviate from safe ranges, enabling rapid interventions such as adjusting feeding, aeration, or cage depth. In rivers and reservoirs, distributed sensor nodes tracking water level, flow velocity, and turbidity can warn of approaching flood events hours in advance, reducing cage losses and escape events. AI-enabled buoy systems and cloud platforms extend these capabilities by analyzing trends, predicting short-term changes in temperature or current velocity, and supporting decision rules for stocking, harvest timing, and emergency response. For grouper farms, integrating these technologies supports more precise feeding, reduces stress-related mortality, and stabilizes water quality under increasingly variable climatic and anthropogenic pressures.

Green aquaculture for cage-cultured grouper focuses on closing nutrient loops, cutting waste emissions, and lowering the carbon footprint of production. Nutrient budgeting has shown that conventional cages release substantial nitrogen and phosphorus per tonne of fish, driving eutrophication when unmanaged. Integrated multitrophic aquaculture (IMTA), aquaponics, and loop bio-phytoremediation systems offer effective remedies by coupling fed species with extractive organisms. Co-culturing fish with bivalves, macroalgae, or filter-feeding invertebrates enhances nutrient retention, while hydroponic or wetland plants remove dissolved inorganic nitrogen and phosphorus from recirculated water with high efficiency. Field systems combining floating net cages, physical filters, and phytoremediation plants have achieved large reductions in nitrate, phosphorus, and organic matter discharged to surrounding waters. At the pond and system scale, IMTA-aquaponic configurations have improved feed conversion ratios and raised nitrogen and phosphorus utilization above 80%, transforming fish waste into additional biomass of finfish, shellfish, and vegetables. For marine grouper systems, floating treatment wetlands planted with halophytic species can simultaneously lower dissolved inorganic nitrogen and reduce CO_2 and N_2O emissions, providing co-benefits for water quality and greenhouse gas mitigation. Complementary measures include reformulation of feeds to reduce phosphorus content without compromising growth, optimization of stocking density to balance production and stress, and adoption of energy-efficient equipment to curb fuel and electricity use. Together, these green technologies and emission-reduction practices reposition grouper cage culture on a trajectory that aligns productivity with ecological resilience and climate goals. Maintaining suitable water quality in cage-cultured grouper requires aligning production intensity with ecological carrying capacity, supported by spatial planning and robust farm-level practices. Real-time monitoring and early warning systems enable rapid responses to environmental fluctuations and operational risks. Green technologies-ranging from IMTA and phytoremediation to low-phosphorus feeds and energy-efficient operations-substantially reduce nutrient emissions and greenhouse gas outputs, creating a more sustainable and resilient grouper aquaculture sector.

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Conflict of Interest Disclosure
The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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