

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