

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