

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.