

7.3 Evolution of sediment conditions and micro-ecosystems

Higher stocking density modifies the benthic environment by increasing biodeposition and strengthening pelagic-benthic coupling. In *C. farreri* culture, daily biodeposit production in early summer was estimated at $7.78 \text{ g} \cdot \text{m}^{-2}$, with associated carbon, nitrogen, and phosphorus transfer to the benthos, indicating a substantial enhancement of material flux from the water column to sediments. This process is ecologically significant because concentrated bivalve biomass can generate intense particulate organic matter deposition on surrounding sediments, even though the local impact depends on subsequent resuspension and transport.

Sediment responses then feed back to the culture environment through oxygen demand, nutrient release, and microbial restructuring. In a coastal scallop farming area affected by summer hypoxia, sediment in the mariculture zone showed higher oxygen consumption than non-mariculture sediment, supporting a direct link between scallop biodeposition and dissolved oxygen loss in overlying water. Bivalve-related bioturbation can also shift sediment microbial function: moderate clam density increased nitrogen-cycling activity and the abundance of related genes in IMTA sediment, whereas bivalve culture in another IMTA system was associated with higher dissolved oxygen, lower ammonia and nitrite, and more nitrifying and denitrifying bacteria in the bivalve area (Yuan et al., 2022; Kong et al., 2023). Overall, the density effect in *Chlamys farreri* is inseparable from water-environment regulation: higher density elevates oxygen demand, intensifies food depletion, and accelerates biodeposition, while water exchange and sediment processing determine whether those pressures remain tolerable or become growth- and survival-limiting.

8 Case Study: Density Optimization Practices in Different Aquaculture Systems

8.1 Density optimization in offshore raft culture systems

Offshore raft or suspended longline systems optimize stocking density by using stronger water exchange to buffer competition, while still requiring density restraint to maintain growth and survival. In *Chlamys farreri*, offshore culture in Sungan Bay produced higher growth and survival than inshore culture, and the best offshore performance occurred at 20-30 individuals per disc, which was attributed to higher current speed and improved food supply. This aligns with broader suspended-culture evidence showing that low net coverage and favorable temperature windows improve shell growth and survival, with recommended stocking below about 33% coverage and preference for bay mouths or estuarine mouths where physical conditions are more favorable. The practical rationale for lower offshore densities is not only biological but also operational. Meta-analysis across Northwest Atlantic scallop farms found that stocking density was the second most important determinant of growth and its effect was consistently negative, indicating that even productive offshore systems cannot fully offset crowding penalties. At the farm scale, density optimization must also balance growth against labor and equipment costs, because low-density net stocking increases the number of nets that growers must service and therefore raises handling costs and infrastructure demand. For this reason, offshore density optimization is best treated as a compromise between maximizing individual growth and minimizing the spatial and economic costs of sparse stocking.

Offshore density control is also constrained by local hydrodynamic modification caused by the culture system itself. Modeling from Sungan Bay showed that high-density suspended aquaculture weakened current velocities in culture layers by about 65% in scallop zones and reduced bay-scale water-exchange ability, implying that excessive facility density can erode the flushing advantage that offshore sites initially provide (Liu and Zhang, 2022). Similar environmental comparisons in Japanese scallop farming showed that site suitability peaks were associated with current effects, whereas extreme summer temperatures above 24°C were linked to poor culture performance and mortality, reinforcing that offshore density targets must be adjusted to site-specific circulation and thermal regimes (Ara et al., 2016). A second offshore lesson is that commercially optimal density is not always the biologically lowest density. In juvenile sea scallops, maximum growth occurred at 50 scallops per net, but growth at 100 per net was only slightly lower and was considered commercially preferable, because a moderate increase in density improved space use without causing a major decline in performance. A similar pattern was reported for queen scallops in Galicia, where maximum growth occurred at 25 scallops per tray, yet 50-100 per tray was recommended on a commercial scale because growth losses remained small while output per unit system increased.