

Space limitation still matters, but it usually acts as a secondary constraint that amplifies feeding interference once individuals become larger or shell contact becomes frequent. Meta-analysis of net-cultured sea scallops found that shell contact can inhibit feeding and that relative growth rate decreased by about 55% as areal coverage increased from 1% to 50%, showing that physical crowding can intensify the ecological effects of food competition. Similar patterns have been reported in other bivalves, where increasing body size raises both food demand and space demand, so density effects often become more apparent later in the culture cycle rather than immediately after stocking.

3.2 Water exchange and local microenvironment changes

Stocking density also alters the hydrodynamic and chemical microenvironment experienced by cultured scallops because dense culture structures slow water movement and reduce the renewal of food and oxygen inside the culture unit. An ecosystem model for a kelp-bivalve bay showed that aquaculture structures can significantly weaken water-exchange capacity, increasing half-exchange duration from about 7 days without aquaculture to about 16 days with culture present, which means that high-density farming can modify local flushing at the bay scale (Liu et al., 2025). At the operational scale, water-exchange experiments in scallop larviculture further showed that higher exchange rates improved larval yield and allowed high densities to be maintained more effectively, indicating that the ecological impact of density depends strongly on the rate at which the surrounding water is renewed (Sühnel et al., 2024).

These hydrodynamic effects are important because they shape food delivery, metabolic waste dilution, and local oxygen conditions simultaneously. In sea scallop culture, current speed was identified as an important factor in food delivery, although excessively strong flow can also inhibit filtration, so the relationship between density and performance depends on whether local flow supports or restricts seston replenishment. Evidence from broader intensive aquaculture systems points in the same direction: as stocking density rises, dissolved oxygen tends to fall while ammonia rises, showing that inadequate water renewal converts density stress into a local microenvironment problem rather than a simple numerical one (Firayani, 2024).

3.3 Waste accumulation and ecological feedback effects

A third ecological driver of stocking density variation is the accumulation of feces, pseudofeces, and other biodeposits generated by dense populations of filter feeders. In *Chlamys farreri* culture, filtering and biodeposition can greatly enhance the transfer of suspended matter, carbon, nitrogen, and phosphorus from the water column to the seabed, and sedimentation rates at culture sites have been measured at about 2.46 times those at reference sites (Zhou et al., 2006). This means that higher stocking densities do not simply increase production; they also strengthen benthic-pelagic coupling, changing the ecological context in which scallops themselves continue to feed and grow.

These feedbacks can be beneficial at moderate intensity but harmful when organic loading exceeds local assimilative capacity. On one hand, suspended bivalve culture can function as a biofilter and help mitigate eutrophication by removing seston from nutrient-enriched waters. On the other hand, field and mesocosm studies of bivalve biodeposition show that increasing farm density promotes organic matter accumulation, anoxic sediment development, and reduced benthic infaunal abundance, while species-specific biodeposit reactivity can also elevate dissolved inorganic carbon and ammonium production during decomposition (Murphy et al., 2019; Lavoie et al., 2024). Overall, variation in optimal stocking density for *Chlamys farreri* is controlled by the interaction of competition, water exchange, and waste feedbacks. For this species, density should therefore be understood as an ecological threshold problem: once food depletion, reduced flushing, and biodeposition accumulation exceed local carrying capacity, scallop growth and survival begin to decline.

4 Experimental Design and Rationale for Density Gradients

4.1 Principles for setting stocking density gradients

Stocking density gradients should be set to span a real biological contrast rather than only small numerical differences, because scallop growth usually declines progressively as density increases. Gradient levels should also reflect practical culture ranges used in scallop farming experiments, such as the six-density design from 136 to 818 spat m⁻² used in juvenile giant scallops, which allowed growth, yield, and survival to be compared across a broad