

ponds, increasing clam density significantly lowered pH, chlorophyll-a, suspended particulate matter, and total nitrogen, but the overall water-quality index first improved and then declined, with the best performance at an intermediate density rather than the highest one (Yao et al., 2025). A similar pattern appears in blood clam-shrimp polyculture, where doubling clam and shrimp density did not significantly impair water quality, indicating that moderate density increases remain environmentally tolerable when system design and feeding are matched to biological demand (He et al., 2025).

Carrying-capacity studies likewise show that culture performance declines when stocking exceeds available food supply or assimilative capacity. In Jiaozhou Bay, ecological modeling indicated that existing bivalve culture was already saturated, with high mortality rates, and recommended reducing Manila-clam seeding density to about 700 ind.·m² to improve sustainability and culture efficiency. More recent ecosystem-quality modeling estimated shellfish ecological carrying capacity at 33.58 t/km², about 73.3% of the current stocking density, further showing that optimal density is below present practice when ecosystem structure and function are used as evaluation criteria (Song et al., 2025).

6.3 Relationships between density stress and disease risk

High stocking density can increase disease risk indirectly by creating chronic stress, reducing growth, and weakening survival under unfavorable conditions. A broad review of shellfish physiology concluded that chronic stress, especially when combined with microbial, chemical, or abiotic stressors, increases infectious-disease risk, exacerbates morbidity, and reduces recovery potential (Coates and Söderhäll, 2020). In cultured Manila clams, increasing density reduced shell growth consistently and, under less favorable site conditions, sharply increased mortality at the highest density, indicating that density stress lowers resilience when environmental quality deteriorates (Bordignon et al., 2021).

Mechanistically, disease vulnerability under density stress is plausibly mediated through stress-induced disruption of immune processes. Shellfish health assessments increasingly rely on haemocyte counts, enzyme activities, and related biomarkers because stressed individuals may appear externally normal while already showing immunomodulation and reduced immunocompetence. Experimental work on clams further shows that environmental stress can alter metabolic and immune-enzyme responses within hours, and pollutant exposure can suppress hemocyte-based immunity and thereby reduce the capacity to resist external challenges, supporting the view that dense culture becomes most hazardous when it coincides with other environmental stressors (Huang et al., 2025). Overall, stocking density affects hard-clam culture environment and health status through threshold-dependent changes in sediment processes, nonlinear effects on water quality and carrying capacity, and stress-mediated increases in disease susceptibility. The evidence supports managing density below ecological saturation points rather than maximizing biomass per unit area.

7 Density Optimization Techniques and Management Strategies

7.1 Appropriate stocking density allocation at different culture stages

Stocking density should be allocated by culture stage because the biological constraints of larvae, nursery juveniles, and grow-out clams are different. In hatchery culture, excessively high larval density suppresses growth and delays settlement, whereas moderate density provides a better balance between output and seed quality in *Meretrix meretrix*. A similar pattern was reported for *Ruditapes decussatus*, where moderate larval and settlement densities improved survival, growth, and fixation relative to the highest treatments (Azirar et al., 2024). During juvenile and pre-fattening stages, density can be raised above hatchery levels, but only within the carrying capacity of the rearing system. In suspended pre-fattening of Manila clam, 30,000 clams·m⁻² was recommended because it maintained a good proportion of sowable seed while reducing the risk seen at 50,000 clams·m⁻² under less favorable water conditions (Bordignon et al., 2021). For intermediate culture more broadly, lower juvenile densities consistently produced better growth and survival, as shown in raft-cultured razor clams (Figure 3).

At grow-out stage, suitable density should be set not by seed availability alone but by growth-survival-profit tradeoffs. In earth-pond culture of *Meretrix lyrata*, 150 individuals·m⁻² produced the highest economic return, even