

8.2 High-density management strategies in hatchery/nursery phases

During hatchery and nursery phases, density optimization relies less on simple density reduction and more on stage-specific control of water exchange, size grading, and timely thinning. In recirculating larviculture of *Nodipecten nodosus*, low density combined with high water exchange gave the highest survival and competent-larvae yield, whereas high density with high exchange produced the greatest total larval number per tank volume, showing that hatchery density can be raised if water renewal is strong enough to stabilize performance (Sühnel et al., 2024). In *Argopecten ventricosus*, early larval production was improved by starting at 6 larvae m/L and reducing density to 2 larvae m/L by day 7, indicating that high initial density can be useful if it is followed by planned thinning before crowding suppresses growth. Nursery systems also manage high density through unit configuration and animal redistribution rather than through a fixed low-density rule. In *Pecten fumatus* upwelling nurseries, growth declined progressively on downstream screens, but daily rotation of screen position eliminated much of this uneven growth and increased biomass gain, while the practical upper stocking limit for maintaining maximum growth was about 70% screen coverage. Land-based raceway nursery for *Pecten maximus* provided a different strategy: an intermediate nursery stage increased survival enough to offset roughly 20% higher operating cost, making denser and more controlled pre-sea rearing economically attractive when post-transfer losses are otherwise unstable.

Another common nursery strategy is to reduce the biological consequences of high density by controlling size structure and deployment method. In Catarina scallop longline culture, low density produced faster growth in nursery and intermediate phases, but homogeneous size selection at each stage helped standardize later performance and survival remained above 91% overall. In farm-based sea scallop nurseries, season, initial size, and gear type affected growth and recovery more strongly than the two collector-bag densities tested, showing that density management in early stages must be integrated with deployment timing and nursery design rather than treated in isolation. High-density nursery practice also carries a health cost if crowding is prolonged. In noble scallops, long-term overcrowding caused higher mortality, slower growth, higher bacterial load, and weaker antibacterial capacity, while a separate study showed lower survival and suppressed MyD88-related immune expression under high density (Liu et al., 2019). These results indicate that hatchery or nursery systems can use high densities temporarily, but only when exchange, handling, and duration are controlled tightly enough to prevent chronic stress from converting space efficiency into immunological risk (Feng et al., 2023).

8.3 Comparative analysis of density adaptation across different marine environments

Across different marine environments, density adaptation depends on how local food supply, current speed, temperature, and carrying capacity modify the cost of crowding. In Jiaozhou Bay, ecological modeling concluded that scallop stocks exceeded carrying capacity, that mortality rose significantly above about 50 individuals per layer, and that recommended density should be reduced to 280 individuals per cage. By contrast, in the offshore area of Sungo Bay, reducing *C. farreri* seeding density to around 20 individuals per layer was reported to improve both ecological conditions and culture efficiency, illustrating that optimal density becomes lower where the management goal includes ecosystem recovery as well as production (Liu et al., 2021). Temperature and depth further shift density tolerance across regions. In Galicia, queen scallop growth was lower at 2 m than at 7-12 m because surface waters had lower salinity in winter, higher summer temperatures, and lower chlorophyll a, showing that a nominal density can become suboptimal when vertical habitat quality declines. Bay scallop nursery studies likewise found that density effects depended on scallop size, with 16-17 mm juveniles tolerating up to 7500 m⁻² and 24-25 mm juveniles tolerating up to 2500 m⁻² without substantial growth reduction, so density standards should scale with body size rather than remain fixed through ontogeny.

Comparative evidence therefore supports an adaptive rather than universal density framework. Some systems can sustain relatively high densities with little survival penalty, as seen in giant scallops where survival remained 91% across 136-818 spat m⁻² and in sea-based nursery bags where two tested densities did not significantly alter recovery. Other systems are much less tolerant, especially when warming, poor flushing, or prolonged overcrowding interact, so density must be reduced proactively according to local environmental ceilings rather than only according to infrastructure capacity (Liu et al., 2021). Overall, density optimization in different aquaculture systems is not a