

stressor that affects endocrine status, energy allocation and disease resistance. In *A. japonicus*, increasing density altered cortisol, lactate and glucose profiles, with small individuals showing significantly higher cortisol at high densities and greater changes in lactate and glucose, indicating elevated stress and energy consumption that ultimately reduced growth and biochemical reserves. Under bacterial challenge and acute temperature decrease, high density increased morbidity and inhibited righting and feeding behaviors, while antioxidant (SOD) and metabolic (PK) enzymes were elevated, helping explain decreased stress resistance and higher mortality risk at crowded conditions (Tian et al., 2025).

6.3 Evaluation of correlations between environmental factors and growth performance

Environmental conditions interact with density to shape growth responses, particularly via organic loading and water quality. In open-water IMTA, *Holothuria poli* stocked under fish cages at sites 10-25 m from the pens had positive SGR (0.18%-0.20%/d), whereas animals at a reference site showed no average growth; however, mass mortalities occurred directly beneath cages due to smothering by settled wastes, despite dissolved oxygen levels above lethal thresholds (Cutajar et al., 2022). In *H. scabra*-seaweed co-culture, sediment TOM and TOC decreased at medium sea cucumber density but accumulated at low and high densities, and growth rates were highest at low density, indicating that both benthic food supply and self-induced organic enrichment mediate density-growth relationships. Temperature is another key covariate, with both optimal windows and thresholds interacting with density. For California sea cucumbers, auricularia larvae showed highest SGR and metamorphosis at 16-18 °C, and survival peaked at 16 °C, suggesting that sub- or supra-optimal temperatures could narrow the density range that supports good growth and metamorphosis. For a fast-growing *A. japonicus* strain, rapid growth and pronounced density-related variation occurred at an average of 19.7 ± 1.3 °C, illustrating that near-optimal temperatures can amplify both growth and inter-individual differences as density rises.

7 Case Study: Evaluation of Sea Cucumber Growth Under Practical Stocking Density Management

7.1 Analysis of practical applications of different density management models at a typical farm

On tropical farms culturing *Holothuria scabra*, producers commonly combine earthen nursery ponds, community sea pens and sea ranching areas, adjusting stocking densities across units to balance growth, survival and operational costs. Earthen ponds are reported as the most effective units for nursery rearing juveniles to stocking size, with growth and survival to market size considered favorable, but further improvements are expected through experiments on stocking density, feeding regimes and pond management. Sea pens and sea ranching are used as grow-out and stock-enhancement models, but they differ in security and density control: pens confer ownership yet incur costs for materials and surveillance, whereas ranching spreads animals over large leased areas at low per-area density, trading density control for lower infrastructure investment. At integrated multi-trophic aquaculture (IMTA) sites, density management must simultaneously support growth and bioremediation. A Mediterranean fish farm co-culturing *Holothuria poli* below cages showed that sea cucumber survival and growth depended on cage positioning and organic load, with mass mortalities directly under the cage due to smothering by settled wastes, and better specific growth rates at moderate distances from the farm (Cutajar et al., 2022). Practical density management on such farms therefore relies on matching stocking levels and cage placement to modeled waste footprints, ensuring that sea cucumbers receive sufficient organic inputs without exceeding local benthic carrying capacity (Figure 2) (Sadoul et al., 2022; Grosso et al., 2023).

7.2 Production issues and optimization measures under high-density culture conditions

High-density culture is attractive for maximizing output per unit area but frequently introduces production problems related to crowding stress, disease, and water and sediment quality. In *Apostichopus japonicus*, high stocking density increased morbidity and suppressed feeding under bacterial challenge and acute temperature decreases, while antioxidant (SOD) and metabolic (PK) enzyme activities rose, indicating reduced stress resistance and higher maintenance costs that can depress growth (Tian et al., 2025). Similarly, behavioral and transcriptomic analyses show that chronic high density inhibits long-term feeding, alters neurotransmitter levels and affects lipid and energy metabolism pathways, helping to explain why growth often stagnates or declines when densities exceed critical