

attributed to intensified competition for food and space on or within the sediment. Similar patterns appear in *Holothuria tubulosa*, where juveniles stocked at 6 ind/m<sup>2</sup> achieved substantial weight gain, while those at 30 ind/m<sup>2</sup> exhibited negative growth and spent more time on tank walls, behavior interpreted as escape from crowded, resource-limited sediments. Space utilization efficiency also depends on how individuals partition habitat and cope with physical stressors. On NE Atlantic rocky reefs, *Holothuria arguinensis* densities and size distributions are shaped mainly by the ability to withstand hydrodynamic forces, enabling different size classes to use distinct microhabitats and thereby reduce direct competition for space and resources (Silva et al., 2023). In sea ranching of *Holothuria atra*, low-density cages achieved higher individual weight gain than high-density cages, and overcrowding led to fission and reduced body size, reflecting ecological limits where critical biomass thresholds are determined by available sedimentary organic matter and microphytobenthos production (Hartati et al., 2020; Hartati and Zainuri, 2021).

### 5.3 Interactions between environmental factors and growth responses under different densities

Environmental factors such as temperature, disease pressure and organic loading interact with density to shape growth outcomes and survival. In *A. japonicus*, high-density groups exposed to bacterial challenge or acute temperature decrease showed elevated morbidity, suppressed righting and feeding behaviors, and increased superoxide dismutase and pyruvate kinase activities, indicating that crowding reduces stress resistance and amplifies the negative effects of additional environmental stresses (Tian et al., 2025). Larval stages show similar density-environment interactions: auricularia of *Parastichopus californicus* had reduced specific growth rates and metamorphosis at 8 inds/mL compared to  $\leq 0.5$  inds/mL, and optimal performance occurred only when density and microalgal ration were matched to favorable temperatures (16 °C -18 °C). Water and sediment quality conditions, themselves products of culture intensity, further mediate density effects. In an abalone-*Neostichopus grammatus* IMTA system, higher sea cucumber density significantly lowered nitrite concentrations and, together with tank-cleaning frequency, shaped sludge organic matter and nutrient content, thereby influencing abalone growth even though sea cucumber growth remained unaffected (Onomu et al., 2024). In ponds for *A. japonicus* seedlings, temporal changes in phytoplankton biomass, particulate organic matter and chlorophyll-a provide both food and environmental cues; such dynamics imply that a density suitable at one time may exceed carrying capacity when plankton and particulate food decline later in the season (Wu et al., 2026).

## 6 Growth Responses of Sea Cucumber Under Different Stocking Densities

### 6.1 Comparison of growth differences under various stocking densities

Growth comparisons across densities consistently show that individual performance declines as crowding increases, although the optimum level varies by species and system. In juvenile *Holothuria tubulosa*, mean weight gain was about 29.5 g at 6 ind/m<sup>2</sup> but fell to 3.0 g at 15 ind/m<sup>2</sup> and became negative (-4.4 g) at 30 ind/m<sup>2</sup>, with specific growth rate decreasing significantly as density increased. Similar patterns were observed in *Holothuria scabra* integrated with seaweed, where sea cucumbers at low density (150 g/m<sup>2</sup>) had the highest mean growth rate (0.80 g/d), while growth dropped markedly at high density. For *Apostichopus japonicus*, both tank and field studies indicate that specific growth rate and body weight decline with increasing biomass, and that intermediate densities may be optimal. In a full-sib fast-growing strain, body weight and SGR decreased significantly as density increased from 130 to 220 days, and regression modeling identified an optimal initial density of 24.4 g/m<sup>2</sup> for seedling production. Field grow-out with three size classes showed that small individuals had higher growth rates (0.63%/d) than medium and large across densities, implying that growth responses to density are size-dependent and that density settings should be adjusted as animals grow.

### 6.2 Analysis of density effects on survival rate and health status

Survival generally remains high at low to moderate densities but declines when biomass exceeds system carrying capacity or when high density interacts with other stressors. For *A. japonicus* in indoor tanks, survival stayed between 90%-100% at 1-5 ind per 10 L but dropped to 72% at 10 ind per 10 L, indicating a threshold beyond which crowding compromises survival. In net-cage culture, survival at the highest biomass (850 g/m<sup>2</sup>) was 73%, lower than 78%-89% at 150-600 g/m<sup>2</sup>, again showing density-dependent mortality. High density also acts as a chronic