

H. scabra and *A. japonicus*, net-cage and pond studies suggest recommended juvenile stocking around 80-90 g/m² or moderate biomass levels, with suppressed growth and sometimes increased mortality when densities exceed empirically derived thresholds. However, current density-optimization research is fragmented: many experiments use different size classes, weight metrics and feeding regimes, limiting cross-study comparability and meta-analysis (Ciriminna et al., 2024). Moreover, most work focuses on short-term growth and survival rather than integrating density with bioremediation goals, economic performance and welfare, even though modeling studies show that optimal densities for growth may not coincide with those maximizing waste removal in IMTA (Chary et al., 2020; Ren et al., 2024).

3 Key Factors Determining Stocking Density in Sea Cucumber Culture

3.1 Sea cucumber growth stages and requirements for optimal stocking density

Stocking density must be matched to the life stage of sea cucumbers because growth responses to crowding differ markedly between larvae, juveniles, and adults. Studies on auricularia larvae of *Parastichopus californicus* show that specific growth rate and metamorphosis decline sharply at high larval densities, with optimal performance at or below 0.5 larvae/mL, highlighting the sensitivity of early stages to density-dependent competition for microalgal feed. For nursery phases, juvenile *Holothuria scabra* reared in tanks can achieve very high specific growth rates when provided with appropriate algal diets, but survival and growth still depend on keeping biomass within limits that do not compromise water quality or feed availability (Campo et al., 2022). During grow-out, density-growth relationships are strongly size-dependent, with smaller juveniles often tolerating higher areal densities than larger conspecifics. In *Holothuria tubulosa*, juveniles (~40 g) stocked at 6 ind/m² had markedly higher weight gain and specific growth rate than those at 15 or 30 ind/m², where growth became negligible or negative, indicating a clear optimal density threshold for this size class. Similarly, in *Apostichopus japonicus*, smaller individuals showed higher specific growth rates than medium and large conspecifics across densities, implying that optimal biomass must be periodically adjusted as animals grow to prevent density-induced growth depression and survival losses at high total biomass (e.g., 850 g/m²).

3.2 Influence of culture environmental conditions on density settings

Environmental conditions modulate the density that a given life stage can tolerate, particularly through effects on food supply, sediment quality, and water quality. In integrated mariculture of *Holothuria scabra* with *Eucheuma denticulatum*, low sea cucumber densities produced the highest individual growth rate, while medium densities most effectively reduced sediment total organic matter and carbon, indicating that both growth and bioremediation outcomes depend on interactions between density and organic loading. Similarly, in sea ranching of *Holothuria atra*, stocking time and the development of microphytobenthos on the cage sediments influenced growth, with the second stocking period yielding the highest weight gain at low density, showing how benthic food resources and rearing duration shape effective density limits (Hartati et al., 2020). Water temperature, substrate type, and system design also constrain stocking density. A dynamic energy budget model for *Apostichopus japonicus* emphasized the importance of accurate lower and upper thermal tolerance boundaries because hibernation and aestivation periods create fast-growth and non-growth phases that alter how much biomass a pond or co-culture system can support at different seasons. In land-based IMTA tanks, negative growth of *Neostichopus grammatus* across densities was attributed not to biomass but likely to bare-bottom tanks without sand substrate, underscoring that unsuitable habitat structure can effectively lower the carrying capacity and make even moderate densities unsustainable (Onomu et al., 2024).

3.3 Regulation of carrying capacity by culture models and management measures

Different culture models-ponds, pens, cages, and open-water IMTA-have distinct physical and trophic constraints that define carrying capacity and thus acceptable stocking densities. Modeling work for *Parastichopus californicus* in IMTA systems showed that deposit feeders can substantially reduce particulate organic carbon loading (up to 86%-99%) and strongly enhance their own production beneath finfish and shellfish cages, but only when densities are set within ranges that balance waste supply and benthic assimilation. In field IMTA trials with *Holothuria poli* near Mediterranean fish cages, mass mortalities directly under cages highlighted that exceeding local ecological