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Evaluation of Sea Cucumber Growth Under Different Stocking Densities

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Abstract Sea cucumber aquaculture has become an important sector of the marine farming industry due to the high nutritional and economic value of sea cucumbers. Among the various management practices, stocking density is recognized as one of the most critical factors affecting growth performance, survival, resource utilization, and production efficiency. This paper evaluates the effects of different stocking densities on sea cucumber growth by reviewing the biological characteristics of sea cucumbers, key factors influencing density determination, growth assessment indicators, and the physiological and ecological mechanisms associated with density-dependent responses. Particular attention is given to the interactions among stocking density, feeding behavior, environmental quality, and competitive pressure. The analysis indicates that moderate stocking densities generally promote optimal growth, higher survival rates, and efficient utilization of available resources, whereas excessively high densities may result in increased competition, environmental deterioration, physiological stress, and reduced growth performance. Conversely, excessively low densities may lead to underutilization of culture facilities and decreased production efficiency. A case study of practical sea cucumber farming further demonstrates the importance of density optimization in balancing economic returns and ecological sustainability. The findings highlight the necessity of adopting scientifically determined stocking densities according to culture conditions, developmental stages, and management objectives. This study provides a theoretical basis and practical guidance for improving sea cucumber culture productivity and supporting the sustainable development of the sea cucumber aquaculture industry.
Keywords Sea cucumber; Stocking density; Growth performance; Aquaculture management; Culture sustainability

1 Introduction

Sea cucumbers are high-value invertebrates increasingly farmed to meet growing demand and to reduce pressure on overexploited wild stocks. Aquaculture has become an established industry in parts of Asia, especially China, where large-scale production of *Apostichopus japonicus* and other species now supplies most domestic consumption and supports stock enhancement and ocean ranching initiatives. At the same time, serial overexploitation of global fisheries and sharp declines in wild populations have prompted interest in aquaculture, ranching, and restocking as tools for both production and conservation. In emerging regions such as the Mediterranean and North-East Atlantic, aquaculture is still developing, but is viewed as essential for relieving harvesting pressure and restoring depleted stocks. Stocking density is a central variable in sea cucumber culture because it directly affects growth, survival, physiology, and welfare. Many studies report that growth performance generally declines as density increases, with low to moderate biomasses yielding higher individual growth and high densities often causing growth depression or even negative growth (Ciriminna et al., 2024). Experiments with *Holothuria scabra* and *Holothuria atra* show that low stocking densities in pens or cages produce greater weight gain per individual than higher densities, while survival may remain acceptable across a range of densities (Hartati et al., 2020).

Beyond effects on growth, high densities can act as a chronic stressor, altering behavior, digestion, and stress physiology, and may reduce disease resistance and tolerance to additional stressors in *A. japonicus* (Tian et al., 2024; Tian et al., 2025). Optimal stocking density has implications not only for animal performance but also for ecosystem processes and the environmental footprint of farms. As deposit-feeders and ecosystem engineers, sea cucumbers ingest large amounts of sediment, enhancing nutrient cycling, modulating dissolved oxygen and nutrient levels, and influencing organic matter dynamics in benthic systems. In integrated multitrophic aquaculture, increasing sea cucumber biomass can improve bioremediation of particulate waste and, at moderate densities, reduce sediment organic loading and enhance water quality, but exceeding critical densities may compromise growth yield and alter carbon and nitrogen fluxes (Mei et al., 2022). Modeling work indicates that bioremediation benefits in IMTA are constrained by limits to stocking density, as growth decreases or stops beyond critical biomass levels due to competition for space and food. (Chary et al., 2020). Building on this background, the present study, titled "Evaluation of Sea Cucumber Growth Under Different Stocking Densities," aims to quantify how a defined range of densities affects growth performance and survival under controlled culture conditions. Previous work shows that juvenile and grow-out stages of *H. scabra* and *A. japonicus* exhibit density-dependent growth responses, with specific growth rate and final body weight often declining at higher densities, yet optimal thresholds remain species- and system-specific. This study therefore asks how do different stocking densities influence growth rate, survival, and size variability; and is there an intermediate density that maximizes biomass yield without inducing strong stress responses? Based on prior evidence that low to moderate densities enhance individual growth while very high densities reduce growth and can trigger physiological stress, the working hypothesis is that sea cucumber growth will be highest at intermediate stocking densities, with both lower and higher densities yielding reduced performance (Chary et al., 2020).

Sea cucumber aquaculture is expanding to meet demand and relieve pressure on overfished wild stocks, making efficient and sustainable grow-out practices critical. Evidence from multiple species indicates that stocking density strongly affects growth, survival, physiology, and environmental interactions, with low to moderate densities generally performing best. The planned study will test density-growth relationships in a defined system, with the expectation that intermediate densities will optimize growth while maintaining acceptable welfare and environmental conditions.

2 Literature Review

2.1 Research progress on major sea cucumber culture models and environmental adaptability

Sea cucumber aquaculture has expanded rapidly in China and the tropics, supported by hatchery production and diversified grow-out systems including earthen ponds, dedicated ponds and ocean ranching for *Apostichopus japonicus* and *Holothuria scabra*. Across regions, culture models include hatchery-pond grow-out, sea pens, bottom sea ranching and integrated multi-trophic aquaculture (IMTA), each with distinct constraints on density, food supply and environmental loading (Chary et al., 2020). In Europe and the NE Atlantic, sea cucumber aquaculture is still emergent, with fragmented knowledge on species biology, early life stages and optimal rearing conditions limiting full-cycle farming. Environmental adaptability varies strongly among species in IMTA: some, like *Holothuria poli*, show reduced growth under waste-enriched conditions, whereas others tolerate or benefit from co-culture, emphasizing the need to match species' natural feeding strategies and sediment niches to specific farming systems (Ciriminna et al., 2024).

2.2 Mechanisms by which density stress affects the growth of benthic marine invertebrates

Experimental work with *A. japonicus* shows that high stocking density alters behavior, suppressing feeding over longer periods and modifying neurochemical regulation (elevated GABA), which likely reallocates energy away from growth toward coping with crowding (Tian et al., 2024). Under additional stressors such as bacterial challenge or acute temperature drop, high density elevates morbidity and further depresses righting and feeding responses, suggesting reduced stress resistance mediated by changes in antioxidant and metabolic enzymes (e.g., SOD, pyruvate kinase). Moderate densities can enhance metabolic activity and growth, whereas excessive crowding leads to energy diversion into homeostasis and competition, reducing growth efficiency. (Mei et al., 2022)Similar patterns are inferred for other benthic invertebrates in IMTA, where too low sea cucumber density limits bioremediation, but too high densities compromise survival, feeding and output, underscoring density as a chronic stressor linked to food competition, waste accumulation and water-quality deterioration (Chary et al., 2020; Onomu et al., 2024).

2.3 Current status and limitations of domestic and international research on sea cucumber density optimization

Across culture systems, many studies report higher individual growth at low or moderate densities and growth depression at high densities, but the "optimal" level is highly system- and species-specific (Hartati et al., 2020). For

H. scabra and *A. japonicus*, net-cage and pond studies suggest recommended juvenile stocking around 80-90 g/m^2 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/m^2 had markedly higher weight gain and specific growth rate than those at 15 or 30 ind/m^2, 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/m^2).

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 carrying capacity via high biodeposit flux and suboptimal cage setup can negate growth despite adequate food, emphasizing the need to integrate hydrodynamic and deposition patterns into density decisions (Cutajar et al., 2022; Sadoul et al., 2022). Within each model, management measures such as feeding regime, cleaning frequency, and staged stocking adjust the effective carrying capacity over time. In intensive culture of *Holothuria scabra*, high-quality diets can partially offset density-related growth limitations by improving feed conversion and protein efficiency, but crowding still affects survival, health, and feeding, indicating that management can shift but not eliminate density thresholds. In ranching of *Holothuria atra*, repeated stocking events and monitoring of sediment pigments allowed managers to time low-density stockings to periods when microphytobenthos had recovered, thereby improving growth while maintaining acceptable survival at higher densities, demonstrating how adaptive stocking schedules and habitat monitoring can dynamically regulate carrying capacity in open systems (Hartati et al., 2020).

4 Growth Performance Indicators and Statistical Analysis

4.1 Construction of growth indicator systems (weight gain rate, specific growth rate, survival rate, etc.)

In density and feeding experiments on sea cucumbers and other aquaculture species, growth performance is typically quantified through a set of complementary indicators that capture both absolute and relative changes in body mass and population status. For juvenile *Holothuria tubulosa*, growth was monitored by wet weight and summarized using weight gain (WG), growth rate (GR), specific growth rate (SGR), relative weight gain (RWG), coefficient of variation (CV), and survival rate (SR) over the rearing period. Similar indicator suites have been applied for *Holothuria poli* in long-term integrated multi-trophic aquaculture, where relative weight gain, growth rate, SGR and survival rate were calculated from initial and final wet weights and numbers per cage. These indicators are derived from standardized formulas that facilitate comparison across treatments and studies. For H. poli, RWG is defined as $100 \times (W_2-W_1)/W_1$, GR as $(W_2-W_1)/t$, SGR as $100 \times (\ln W_2-\ln W_1)/t$, and SR as $100 \times (n_2/n_1)$, using initial and final mean wet weight (W_1, W_2), culture duration (t), and animal numbers (n_1, n_2) (Cutajar et al., 2022). In sea cucumber density trials, these metrics have been sensitive to stocking density, with SGR, RWG and SR often declining at higher densities, underscoring their suitability as core indicators for evaluating growth responses to crowding.

4.2 Measurement methods for feeding efficiency and energy utilization indicators

Feeding efficiency in sea cucumbers is commonly evaluated through food conversion efficiency (FCE), protein efficiency ratio (PER), apparent digestibility coefficients (ADCs) and related energy budget components. In a 60-day study on *Apostichopus japonicus*, diets with graded biofloc levels significantly affected SGR, FCE and PER, and allowed estimation of optimal dietary replacement levels using polynomial regression of SGR and FCE. Energy allocation was expressed using a full budget (e.g., $100C = 3.8G + 65.4F + 3.3U + 27.5R$), partitioning ingested energy (C) into growth, feces, excretion and respiration, which revealed how diet altered the balance between growth deposition and metabolic losses.Under combined feeding-frequency and density manipulation, energy budget indicators were further linked to crowding stress. In *A. japonicus*, feed intake, energy intake and feces production rate were significantly affected by both feeding frequency and stocking density, and high density reduced food conversion efficiency and protein efficiency ratio while decreasing apparent digestibility of crude protein and lipid. The same study quantified how crowding shifted energy allocation, with energy for growth decreasing and metabolic energy increasing as density rose, supported by endocrine indicators such as elevated cortisol and lactate.

4.3 Statistical analysis methods (ANOVA, multiple comparisons, and regression analysis)

Analyses of density effects on growth indicators in sea cucumbers and other cultured species rely heavily on ANOVA and multiple comparison procedures to test for treatment differences. For *Holothuria scabra*, two-way ANOVA was used to evaluate the effects of feeding regime and stocking density on total and monthly weight gain, with one-way ANOVA applied to daily weight gain and SGR; significance was set at $P < 0.05$ (Figure 1). Similar designs are widely used in density-growth studies of fish and invertebrates, typically followed by Tukey’s or Duncan’s multiple range tests to identify which stocking densities differ in growth, feed conversion or survival.

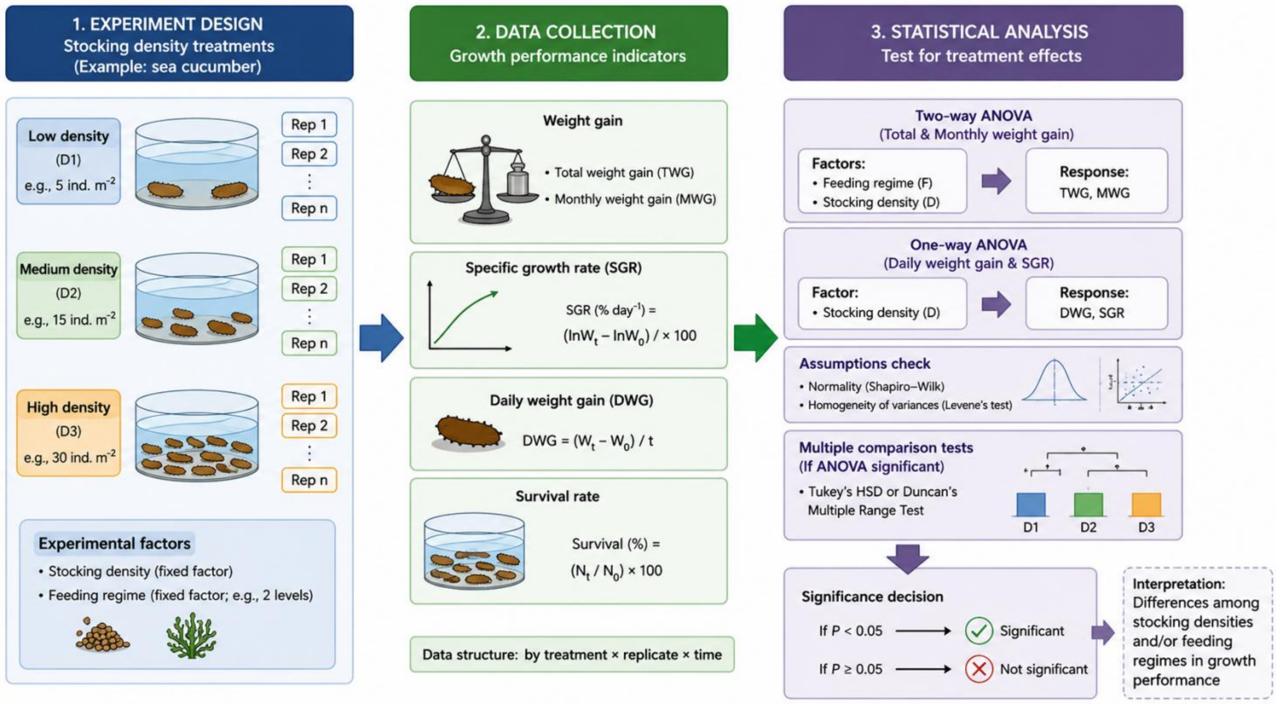

Figure 1 Statistical framework for analyzing stocking density effects on growth performance using ANOVA and multiple comparison tests in aquatic culture systems. Adapted from standard experimental designs in aquaculture growth studies

More advanced approaches combine regression modeling and resampling to capture continuous density-growth relationships. In a floating-cage study on spotted rose snapper, growth was modeled using von Bertalanffy, logistic and Gompertz curves, with model selection via Akaike and Bayesian information criteria, and the logistic model chosen as best (Jurado-Molina et al., 2023). Bootstrap simulations (1,000 runs per density) were then used to estimate the distribution of the instantaneous growth rate parameter (K) for each density, and ANOVA followed by Tukey HSD compared K among densities, revealing an optimal intermediate density not evident from simple length-at-age comparisons (Jurado-Molina et al., 2023).

5 Mechanisms Underlying the Effects of Stocking Density on Sea Cucumber Growth

5.1 Physiological mechanisms underlying the growth-promoting or growth-inhibiting effects of stocking density

Physiological responses to density determine whether stocking promotes or suppresses sea cucumber growth by shaping energy allocation between maintenance and somatic gain. Experiments on *Apostichopus japonicus* show that high densities elevate cortisol and lactate in coelomic fluid, while glucose declines, indicating chronic crowding stress that accelerates energy consumption and reduces resources available for tissue growth. In contrast, moderate densities can enhance metabolic activity and nutrient utilization, as shown by higher metabolizable energy, excretion energy and activities of key respiratory enzymes at intermediate stocking levels, which coincide with superior growth performance (Mei et al., 2022). Behavioral and neuroendocrine adjustments further mediate physiological effects of density on growth. Under high density, *A. japonicus* shows increased crawling in the short term but pronounced long-term inhibition of feeding, directly limiting energy intake and growth potential. Density also alters neurotransmitter profiles: γ-aminobutyric acid (GABA) increases significantly at high density, and transcriptomic changes in lipid and energy metabolism pathways have been observed, suggesting central regulation of behavior and metabolic partitioning that reinforces growth inhibition under crowding (Tian et al., 2024).

5.2 Ecological mechanisms regarding competition for substrate resources and space utilization efficiency

Ecologically, stocking density modifies competition for benthic food and sediment surface, thereby affecting growth and size structure within populations. In integrated mariculture of Holothuria scabra with *Eucheuma denticulatum*, low-density treatments showed the highest individual growth rates, whereas high-density treatments had the lowest, 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^2 achieved substantial weight gain, while those at 30 ind/m^2 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 ≤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^2 but fell to 3.0 g at 15 ind/m^2 and became negative (−4.4 g) at 30 ind/m^2, 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^2) 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^2 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^2) was 73%, lower than 78%-89% at 150-600 g/m^2, again showing density-dependent mortality. High density also acts as a chronic 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 thresholds (Tian et al., 2024). On farms, optimization measures combine density control with husbandry adaptations. In intensive *H. scabra* culture, providing highly nutritious diets and appropriate feeding regimes can partially compensate for food competition at higher densities, improving feed conversion and protein efficiency, though excess crowding still reduces growth. In land-based IMTA tanks, adjusting sea cucumber density and tank-cleaning frequency can optimize bioremediation and co-cultured species performance: higher *Neostichopus grammatus* density lowered nitrite and, at an intermediate cleaning frequency, improved abalone mean weight without affecting sea cucumber growth, illustrating that careful density-management combinations can alleviate some high-density issues (Onomu et al., 2024).

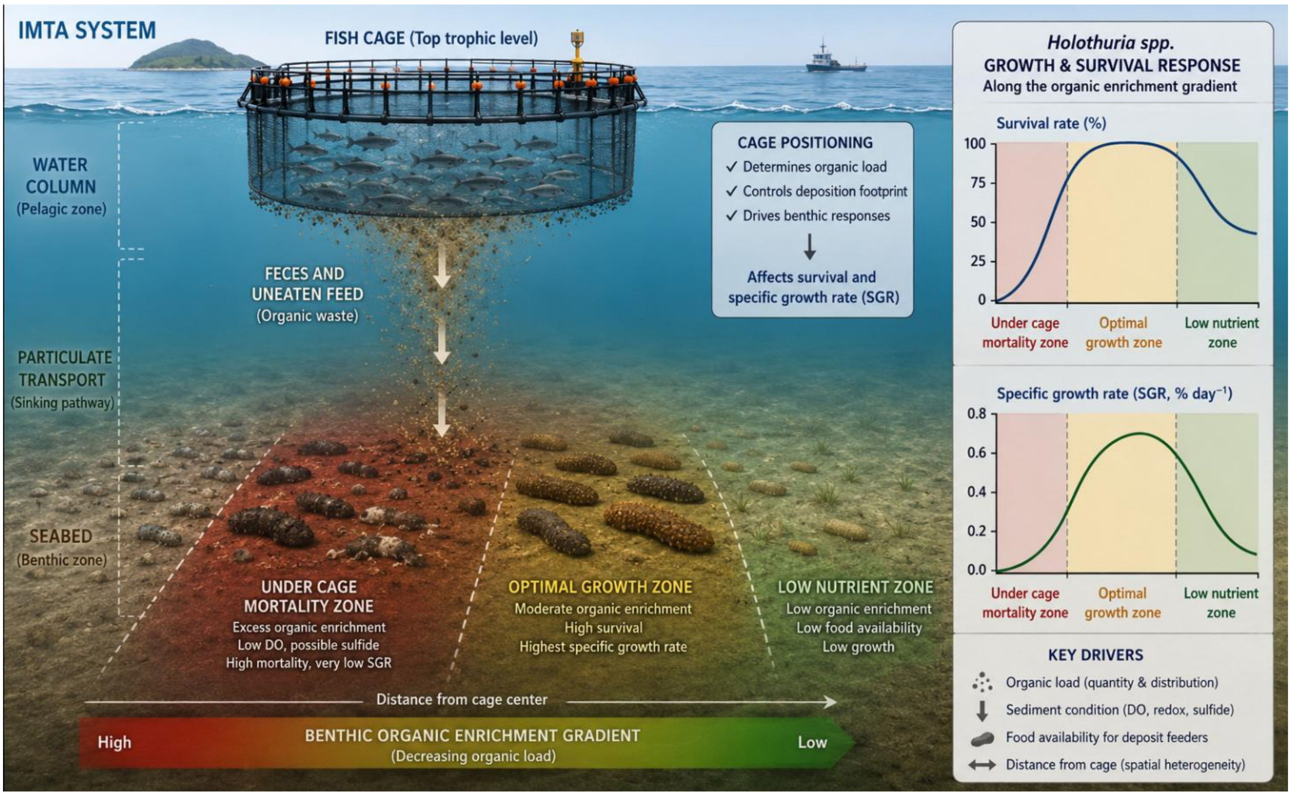

Figure 2 Schematic representation of integrated multi-trophic aquaculture (IMTA) systems showing organic matter deposition gradients and spatial variation in Holothuria spp. growth and survival

7.3 Comprehensive assessment of economic and ecological benefits based on field data

Field studies at community sea-pen farms and ranching sites demonstrate that stocking density management directly influences both economic returns and ecological co-benefits. In tropical *H. scabra* mariculture, cost-benefit analyses show that labour and utility costs can preclude profitability of monoculture pond farming, pushing farmers toward co-culture or lower-cost sea ranching, with profitability shaped by growth to larger body sizes that fetch exponentially higher prices (Azari et al., 2021). At a village-scale farm in Madagascar, pens stocked with *H. scabra* at relatively high densities (~300 g/m^2) significantly increased leaf extension rates of the dominant seagrass Thalassia hemprichii by about 30%, indicating that income-generating sea cucumber farming can simultaneously enhance key coastal habitats (Arnull et al., 2021). At the fish-farm scale, modeling and IMTA assessments reveal trade-offs between stocking density, bioremediation performance and broader environmental impacts. An integrated red drum-*H. scabra* system showed that co-culture reduced eutrophication impacts and net primary production use relative to finfish monoculture, but only slightly lowered net particulate waste because current limits to sea cucumber stocking density constrain bioremediation potential (Chary et al., 2020). More generally, reviews emphasize that exceeding optimal stocking densities may improve local organic matter bioremediation but compromise sea cucumber growth yield, and call for more comprehensive economic evaluations of large-scale IMTA systems including high-value holothurians (Ciriminna et al., 2024).

8 Conclusion

Across species and culture systems, the evidence shows that stocking density exerts a primary control on growth performance, feed utilization and energy allocation in sea cucumbers. Growth rates, specific growth rate and relative weight gain consistently decline as density increases, with high-density groups often exhibiting negligible or even negative weight change, as demonstrated for juvenile *Holothuria tubulosa* and several other Mediterranean species. High densities also modify energy budgets and endocrine status: in *Apostichopus japonicus*, increasing density reduces apparent digestibility, food conversion efficiency and energy for growth, while elevating cortisol and lactate, indicating chronic crowding stress. Stocking density further affects within-cohort variability and health status. For *A. japonicus*, the coefficient of variation in body weight and differentiation in cortisol responses between large and small individuals increase with density, implying that crowding accentuates growth inequality and may predispose smaller animals to poorer performance. Under additional stressors such as bacterial challenge or acute temperature decrease, high density increases morbidity and suppresses righting and feeding behaviors, confirming that crowding not only reduces growth but also compromises stress resistance and overall health.

Despite species- and system-specific differences, a coherent pattern emerges in which low to moderate densities optimize individual growth and survival, whereas higher densities are suitable only for short-term handling. For juvenile H. tubulosa (~40 g) in tanks, 6 ind/m^2 (≈250 g/m^2 yielded substantial weight gain and positive SGR, while 15 ind/m^2 produced negligible growth and 30 ind/m^2 led to negative biomass change, leading to a recommendation of 6 ind/m^2 for grow-out and explicit avoidance of 30 ind/m^2. For H. arguinensis and H. mammata, optimal tank-based densities were identified as 1 ind per 0.2 m^2 and 5 ind per 0.5 m^2 respectively, with critical biomass thresholds (~472 and 988 g/m^2) above which growth ceased, suggesting that both numerical density and biomass should guide management. In pond and net-enclosure systems, optimal densities for *A. japonicus* depend on feeding regimes and management goals. Long-term pond trials fitted with B–N curves identified optimal stocking densities of 22.3 ind/m^2 under feed-supplement and 14.1 ind/m^2 without feed for maximizing net production, reflecting trade-offs between individual growth and total yield. At the industry level, reviews of Mediterranean and NE Atlantic species highlight that medium densities (600-700 g/m^2) can be tolerated briefly for operations such as transfer and cleaning, but high densities and biomass above species-specific critical values should be avoided in routine production to prevent negative growth and health problems.

Current research on stocking density remains constrained by species and regional focus, methodological inconsistency and limited integration with economic and environmental objectives. Systematic review of NE Atlantic and Mediterranean species reveals that most work has concentrated on a few taxa such as H. tubulosa, H. arguinensis and H. mammata, with sparse data for others, and that critical biomass values and recommended densities vary widely, necessitating species-specific tests and standardized protocols. At the same time, large-scale industry reviews from China and the tropics emphasize that despite rapid expansion of sea cucumber farming, many stocking density decisions are still empirical, and there is a lack of well-designed, long-term experiments and meta-analyses to guide best practice across culture models. Future research should couple density manipulation with mechanistic studies on physiology, genetics and behavior, and with multi-objective optimization that includes growth, health, product quality and ecosystem services. Physiological and endocrine work has already shown that density acts as an environmental stressor that alters cortisol dynamics, energy budgets and gene expression, but these insights are rarely incorporated into farm-level management models. Strategic papers on industry development in China call for advances in basic biology, behavioral studies, selective breeding and ecological culture technologies, which together could enable density recommendations that are tailored to strains, environments and integrated multi-trophic systems, supporting both sustainable production and environmental protection.

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