

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/m² (~250 g/m²) yielded substantial weight gain and positive SGR, while 15 ind/m² produced negligible growth and 30 ind/m² led to negative biomass change, leading to a recommendation of 6 ind/m² for grow-out and explicit avoidance of 30 ind/m². For *H. arguinensis* and *H. mammata*, optimal tank-based densities were identified as 1 ind per 0.2 m² and 5 ind per 0.5 m² respectively, with critical biomass thresholds (~472 and 988 g/m²) 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/m² under feed-supplement and 14.1 ind/m² 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/m²) 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.

References

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