

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