

and ingestion were jointly shaped by stocking density and algal ration rather than by either factor alone. These findings indicate that future density trials should be designed around combined gradients of food supply, flow, and biomass loading so that operational thresholds can be defined more realistically for hatchery, nursery, and field systems. The same multi-factor perspective is increasingly necessary under climate stress and variable rearing conditions. Experiments on clam culture under different hatchery environments show that density effects can shift when temperature, salinity, and water exchange are altered, and that better larval performance is often achieved only when these variables are jointly optimized. Climate-driven studies further show that abrupt salinity decline combined with elevated temperature sharply increases mortality and disrupts feeding, especially in juveniles, which implies that density recommendations based on stable conditions may fail under future coastal scenarios. For this reason, future studies should emphasize density-by-environment models, seasonal risk windows, and life-stage-specific tolerance limits, especially for regions where habitat suitability is projected to decline substantially.

A second major development prospect is the use of smart aquaculture technologies to convert density management from periodic manual adjustment to continuous data-driven control. Precision-aquaculture research shows that modern farms increasingly rely on interconnected sensors, cloud platforms, and predictive analytics to monitor environmental change in real time and support operational decisions. Broader reviews of smart aquaculture similarly indicate that machine learning is already being applied to tasks such as growth estimation, grading, disease detection, and water-quality prediction, providing a technical basis for adaptive stocking decisions. In clam farming, these tools could be used to link standing biomass to dynamic measurements of temperature, salinity, oxygen, and food conditions, thereby allowing earlier intervention before crowding depresses growth or survival. However, digital density management will depend not only on algorithm development, but also on solving practical infrastructure constraints. Research on intelligent aquaculture systems shows that reliable online sensing, low-power transmission, and robust networking remain major bottlenecks, especially in harsh aquatic environments where sensor fouling and communication instability reduce data quality. At the same time, operational studies demonstrate that IoT-AI systems can already support real-time monitoring, predictive control, and remote equipment management with high predictive performance, including growth or production forecasts with R^2 values around 0.94. The next step for Manila clam aquaculture is therefore to build digital twins or surrogate models that integrate biomass density, seed size, flow conditions, and water quality into farm-level decision systems rather than treating stocking density as a fixed preset.

Future high-efficiency Manila clam farming will likely combine density optimization, controlled seed production, and environmental accounting across the full production chain. Recent sustainability assessments confirm that Manila clam farming generally performs well environmentally and can even function as a net carbon sink, while still showing clear hotspots in hatchery electricity use, depuration, and fuel consumption during grow-out. This suggests that future density strategies should not aim only to maximize biomass per unit area, but also to minimize energy-intensive losses and improve survival efficiency across nursery and fattening phases. In parallel, the decline of wild seed supply has made hatchery-based systems increasingly important, even though they can raise environmental burdens unless energy sources and seed-production technologies are improved. Another clear trend is the shift toward larger, better-conditioned juveniles and more resilient farming models. Controlled nursery approaches can stabilize seed supply, reduce early mortality, and produce juveniles that are better able to resist predators and environmental stress after transfer. This will become more important as climate change and biological pressures intensify, since projections indicate major reductions in habitat suitability for Manila clam in parts of the Mediterranean, especially around Italy. Sustainable high-efficiency farming will therefore depend on integrating moderate and stage-specific density control with resilient seed systems, low-impact energy use, and ecosystem-service goals such as nutrient removal and carbon sequestration. Future progress in hard clam density research will depend on treating stocking density as a dynamic system variable shaped by environment, technology, and sustainability targets rather than as a single static culture parameter.

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