

Field performance of hatchery produced Asian green mussel *Perna viridis* (Linnaeus, 1758) and strategies to optimise its farming

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Abstract

This study evaluates the field performance of hatchery produced Asian green mussel *Perna viridis* (Linnaeus, 1758) seed across three estuarine sites viz., Ashtamudi, Neendakara, and Vellimon in Kollam District, Kerala, south India, under varying stocking densities. Juvenile spat with an initial mean shell length ranging from 9.3 to 12.6 mm reached commercial harvest size (50.8-82.9 mm shell length) within 6-13 months after deployment under grow-out conditions. During the first three months, specific growth rates peaked at 2.69% day⁻¹ at Ashtamudi, 3.87% day⁻¹ at Neendakara, and 3.71% day⁻¹ at Vellimon, indicating rapid initial adaptation to field conditions. In the 13 month Ashtamudi trial, lines stocked at 2,000 seeds m⁻¹ produced an average yield of 33.4 kg m⁻¹ and a final shell length of 82.9 mm; however, the overall SGR was lowest (0.54% day⁻¹) because relative growth declined as mussel biomass increased overtime. Reducing the stocking density to 1,000 seeds m⁻¹ at Ashtamudi increased the overall SGR to 0.94% day⁻¹ but more than doubled the final survival rate from 37.5 to 77.02%. Among the short term trials (6 months), fastest growth (8.7 mm per month) was recorded at Neendakara, yielding a final shell length of 70.4 mm with a final survival rate of 29.2%. In contrast, Vellimon experienced severe predation because protective sleeve net was not used, resulting in a low final survival rate of 16.79%, despite a steady specific growth rate of 0.91% day⁻¹. These results show that small hatchery produced seed requires effective predator protection to achieve higher field survival, unlike larger and more resilient wild caught seed, traditionally used in mussel farming. Overall, integrating hatchery seed production with optimised stocking densities, seasonal harvesting schedules, and predator exclusion netting, offers a practical strategy to stabilise and expand commercial marine bivalve aquaculture along the south-western coast of India.



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Introduction

Bivalve aquaculture forms a prominent sector of global marine farming, providing an efficient source of animal protein with a low carbon footprint. Among cultivated bivalves, the marine mussels of the genus *Perna* are highly valued commercial species distributed across tropical and subtropical coastal ecosystems (Vakily, 1989). Mussel cultivation in India is restricted to two distinct species viz., the green mussel (*P. viridis*) and the brown mussel (*Perna indica*). The geographic distribution of these species varies along the Indian coastline; *P. viridis* occurs along

both the east and west coasts, whereas *P. indica* is confined to the southern tip of the peninsula, stretching from Kollam in Kerala on the west coast to Tirunelveli in Tamil Nadu on the east coast (Appukuttan *et al.*, 2001; Kripa *et al.*, 2001).

In 2015, mussel farming accounted for 68% of India's total farmed bivalve production of 11,435 t (Geetha Sasikumar *et al.*, 2016). The south-west coast of India, particularly the state of Kerala, serves as the primary hub for mussel farming, accounting for the majority of the country's total production. The sector experienced rapid expansion

following the development of commercial rope farming techniques by the ICAR–Central Marine Fisheries Research Institute (ICAR–CMFRI) in the 1990s (Asokan *et al.*, 2001, Shinoj *et al.*, 2021). This simple, low-cost technology allowed small-scale coastal communities and self-help groups to utilise estuarine backwaters and shallow coastal areas for seasonal mariculture, transforming mussel farming into a vital source of livelihood (Appukuttan *et al.*, 2000).

Despite its historical success, the long term sustainability of Indian mussel aquaculture is constrained by its continued dependence on the collection of wild seed (spat) from intertidal and subtidal rocky habitats. This dependence results in seasonal and spatial variability in seed availability, emphasising the need for reliable hatchery based seed production to support the expansion of the industry (Laxmilatha *et al.*, 2011; Sasikumar *et al.*, 2016; Anil *et al.*, 2024). This complete dependence on wild resources creates substantial vulnerability for farmers. Natural spatfall is highly unpredictable and subject to severe seasonal and interannual fluctuations driven by changing monsoonal patterns, coastal water temperatures, and localised hydrographic currents (Kripa and Mohamed, 2008). In recent years, the scarcity of wild seed has emerged as a major limiting factor, leading to a notable decline in total farmed area and annual production yields across major farming zones (Mohammed *et al.*, 2019; Shinoj *et al.*, 2021). Furthermore, the intensive harvesting of wild seeds from natural beds has raised ecological concerns regarding the degradation of wild broodstock populations and the disruption of coastal biodiversity, while also creating resource conflicts with traditional wild mussel fishers (Geetha *et al.*, 2014). To address these resource limitations and stabilise production, the development of reliable seed production technology is essential. Controlled hatchery production offers a pathway to dissociate the aquaculture sector from its dependence on erratic wild recruitment, ensuring a year round, predictable supply of high quality, uniform spat (Helm *et al.*, 2004). While hatchery protocols for several bivalve species have been successfully commercialised globally, adapting these systems to

tropical species like *P. viridis* requires precise optimisation of larval rearing, feeding regimes, and nursery systems (Laxmilatha *et al.*, 2011).

The Asian green mussel, *P. viridis* is one of the economically important, fast growing mussel species cultured throughout the Indo-pacific region due to its market demand, adaptability to the estuarine and backwater ecosystems and its nutritional value (Kripa and Mohamed, 2008, Laxmilatha *et al.*, 2011). Considering this importance, the Vizhinjam Regional Centre of ICAR–CMFRI, has recently standardised hatchery techniques for the mass production of *P. viridis* spat (Anil *et al.*, 2022). However, evaluating the commercial viability of these hatchery produced stocks requires field validation. It is necessary to assess how these seeds perform under natural estuarine and backwater conditions, particularly regarding their growth, survival rates, and physiological adaptation to fluctuating environmental variables such as salinity and temperature. This study evaluates the field performance of hatchery produced *P. viridis* seed across three geographically and ecologically distinct stations within Ashtamudi Lake, a major bivalve farming estuary in Kerala, South India.

Materials and methods

Experimental sites and seed production

Spat of the Asian green mussel, *P. viridis* were produced under controlled conditions at the bivalve hatchery facility of the Vizhinjam Regional Centre of ICAR–CMFRI, Kerala, India. The mass production of seed followed established institutional guidelines, encompassing broodstock selection, conditioning, induced spawning, larval rearing, and spat rearing, as outlined by Anil *et al.* (2022). The subsequent field performance trials were carried out across three distinct ecological zones viz., Ashtamudi (Station 1, S1: 8°57'51"N; 76°35'56"E); Neendakara (Station 2, S2: 8°56'04"N; 76°33'11"E) and Vellimon (Station 3, S3: 8°57'59"N; 76°37'42"E) situated within the Ashtamudi Lake, in the Kollam District of Kerala (Fig. 1).

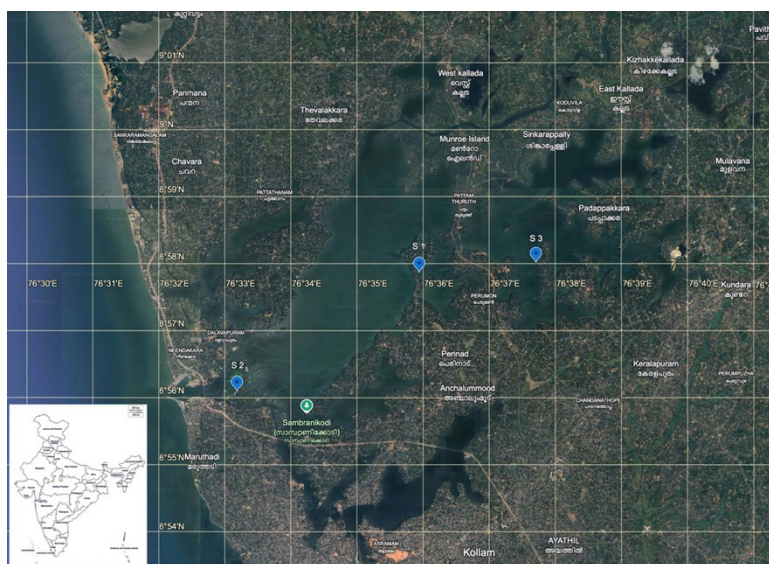


Fig. 1. Map of Ashtamudi Lake, showing the experimental stations, S1-Ashtamudi; S2-Neendakara and S3-Vellimon

Field deployment and cultivation protocols

Ashtamudi (S1)

Two consecutive trials were initiated at Ashtamudi to test different culture parameters. The initial experiment commenced in May 2022 and concluded in June 2023, spanning a 13 month grow-out period. The mussel seeds used had an average shell length of 12.6 ± 1.71 mm and a mean total weight of 0.13 ± 0.04 g. The stocking density was 2000 nos. m^{-1} . These were attached to 1m long cultivation lines consisting of a 4 mm nylon core wrapped in coir (coconut fibre) (Fig. 2). To protect the thin-shelled hatchery spat from natural predators, each seeded line was enclosed within a protective outer netting (Fig. 3). A total of 24 lines were suspended approximately 15 cm below the surface from the structural framing of a floating cage used concurrently for pearl spot (*Etroplus suratensis*) farming. The second trial at this station ran from January 2023 to July 2023 to evaluate a reduced stocking density. Here, smaller spat measuring 9.3 ± 0.94 mm in shell length and 0.097 ± 0.004 g in weight were stocked at a density of 1,000 seeds m^{-1} using 12 cultivation lines.

Neendakara (S2)

The field trial at S2 was conducted between December 2022 and June 2023 at a stocking density of 2,000 seeds m^{-1} across 12 mesh-protected lines. The initial size of the seed averaged 9.5 ± 1.12 mm in shell length and 0.1 ± 0.01 g in weight. The lines were initially suspended from a small floating assembly constructed using galvanised iron (GI) pipes and styrofoam blocks, positioned inside a tide-fed aquaculture pond. Water temperatures in the pond ranged from 24 to 28°C during December and January, before increasing beyond 29°C by late February. By March, critical conditions arose due to seasonal water level depletion, elevated water temperatures reaching 34°C, and heavy organic loading from concurrent finfish stocking, which turned the water to dark brown colour. To prevent mortality due to elevated temperature (34°C) of pond water, all cultivation lines were relocated in March to an adjacent open backwater channel where they remained until final harvest in July.



Fig. 2. Seeded mussel ropes

Vellimon (S3)

At S3, the field trial was maintained from December 2022 to June 2023 using a stocking density of 1,000 seeds m^{-1} . Spat with an initial mean length of 9.5 ± 0.97 mm and weight of 0.095 ± 0.01 g were attached to six lines and suspended from the perimeter of an *E. suratensis* culture raft. Unlike the previous stations, no protective netting was wrapped around these lines, leaving the hatchery seed fully exposed to potential wild predators.

Environmental data collection

Hydrographic parameters at each station were monitored at monthly intervals to track environmental variations. Water temperature was measured with a calibrated digital thermometer, while salinity levels were determined using a hand-held refractometer (Atago, Japan). Dissolved oxygen was estimated via the standard Winkler titration method. Water pH was monitored using a portable pH meter (Horiba, Japan). To determine primary productivity, water samples were analysed spectrophotometrically for chlorophyll-a concentration following the methods described by Parsons *et al.* (1984). Mussels ($n=20$) were sampled monthly to record shell length and total weight. Measurements were taken to the nearest millimetre (mm) and gram (g). Percentage survival was calculated using the formula:

$$\text{Survival (\%)} = (N_f/N_0) \times 100$$

No. represents the initial number of mussel seeds stocked and N_f is the final number of mussels harvested. The specific growth rate (SGR) of *P. viridis* was calculated to assess the growth performance of mussels during the culture period. SGR expresses the percentage increase in body weight per day and was determined using the logarithmic difference in weight over time, as per standard methods used in bivalve growth studies. SGR was determined using the following formula:

$$\text{SGR (\% day}^{-1}\text{)} = (\ln L_t - \ln L_0)/t \times 100$$

SGR = Specific growth rate (% per day)

where, L_0 = Initial mean length of mussels (mm); L_t = Final mean



Fig. 3. Seeded ropes covered with protective net

length of mussels (mm); t = Duration of the culture period (in days);
 $\ln$ = Natural logarithm

Data were analysed statistically to compare growth rates, survival and production across locations and treatments.

Results

Ashtamudi (S1)

Grow-out trial 1

This trial commenced in May 2022. The hatchery produced spat successfully attached to the cultivation ropes, maintaining steady development. At the time of deployment, the seed measured 12.6 ± 1.71 mm in mean shell length and weighed 0.13 ± 0.04 g. Due to the high stocking density of 2,000 individuals per meter,

the mussels clustered tightly along the rope (Fig. 4, 5) as their biomass expanded. The stock successfully survived a low salinity depression down to 10 ppt during the July monsoon period without experiencing high initial mortality. By the sixth month of cultivation, the mussels attained a mean shell length of 55.9 ± 6.08 mm and an average total weight of 9.52 ± 4.16 g with shell length increase of 7.2 mm per month (Fig. 6a, b). At the final harvest in June of the following year, marking a total rearing period of 13 months, the bivalves reached an average shell length of 82.9 ± 7.85 mm and a mean total weight of 44.55 ± 5.8 g. This growth pattern equates to a mean monthly shell length increase of 5.4 mm over the 13 month grow-out period.

Ambient water temperature varied from a low of 20°C in August to a maximum of 32°C in February (Fig. 7). Salinity fluctuated from its minimum of 10 ppt during the July monsoon up to 29 ppt in March. Dissolved oxygen concentrations remained within a range of 4.2 and 5.17 mg l⁻¹, while pH values ranged between 7.6 and 8.4.



Fig. 4. Uniformly attached mussel seed



Fig. 5. Mussel growth at harvest

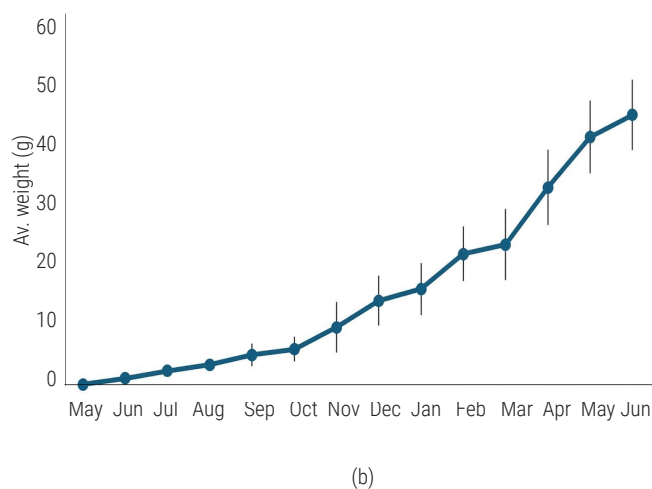
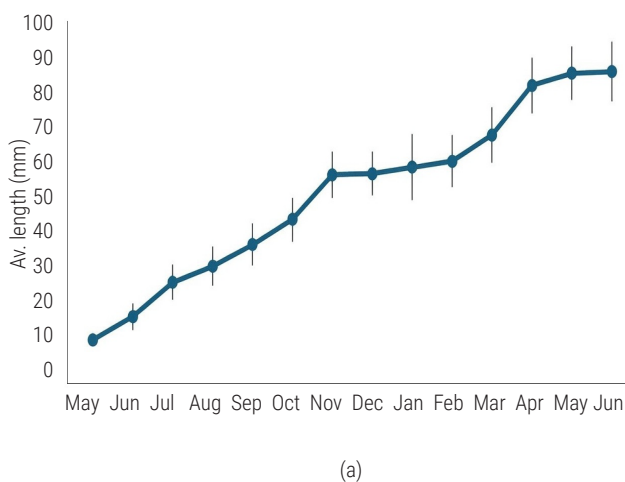


Fig. 6. Growth of mussel in (a) Length (mm) and (b) Weight (g) at Ashtamudi (S1)

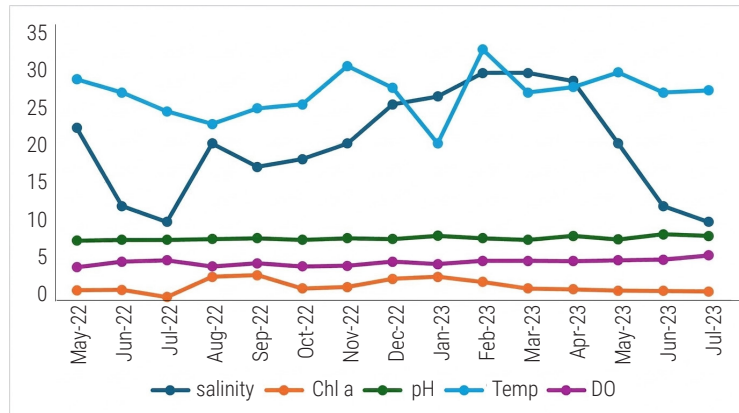


Fig. 7. Monthly variation in water quality parameters at Ashtamudi

Chlorophyll *a* values ranged between 0.41 to 3.2 µg l⁻¹, with peak concentrations recorded in September. At the conclusion of this 13 month trial, crop yields ranged from 15 to 41 kg m⁻¹, resulting in an overall average production of 33.4±9.03 kg m⁻¹. The final survival rate at harvest stood at 37.5±10.1%. The monthly SGR for shell length fluctuated between 0.02%-1.56% day⁻¹, with a trial average of 0.54±0.53 day⁻¹.

Grow-out trial 2

During the second trial at the Ashtamudi site, the stocking density was reduced to 1,000 individuals per meter. The seed attached to the lines exhibited a spaced and distant distribution along the rope compared to the denser positioning observed in the 2,000 seeds m⁻¹ rope. The stock grew from an initial average shell length of 9.3±0.94 mm and a total weight of 0.097±0.004 g to reach 50.9±5.3 mm in shell length and 9.49±2.53 g in total weight by the end of six months. Notably, the first three months of field deployment exhibited an exceptionally high growth, with the specific growth rate peaking at 2.69% day⁻¹. The mussels reached a peak mean weight of 15.71±2.67 g in the fifth month before experiencing a weight decline in July. Over this 6-month time, the average growth rate in shell length was calculated at 6.9 mm per month. This monsoon drops in individual biomass coincided with a drop in water salinity and an increase in mortality, as evidenced by empty, open shells remaining on the ropes. The monthly SGR for this lower density treatment ranged from 0.04-2.69% day⁻¹, with an overall average of 0.94±1.12% day⁻¹. Total production values ranged between 4.8 and 9.89 kg m⁻¹, generating a mean final yield of 7.2±1.7 kg m⁻¹. The final survival rate at harvest was 77.02±18.87%. Delayed harvesting past the pre-monsoon window caused biomass loss and lowered total potential yield.

Neendakara (S2)

At the Neendakara station, the cultivation trial was conducted over a 7-month period (December 2022 to July 2023) using mesh-protected lines stocked at a density of 2,000 mussels m⁻¹. The seeds were initially reared within a tide-fed aquaculture pond utilising a small floating assembly supported by Styrofoam floats. The initial size of the seed averaged 9.5±1.12 mm in shell length and 0.1±0.01 g

in total weight. During the initial pond-rearing phase, the mussels demonstrated better growth, due to the high primary productivity; the specific growth rate during the first three months peaked at a maximum of 3.87% day⁻¹. From December through January, water temperatures in the pond ranged from 24 to 27°C, rising above 29°C by late February. By March, critical hydrographic boundaries arose as seasonal water levels depleted; ambient temperatures rose to 32°C and heavy organic loading from concurrent finfish stocking turned the water to dark brown in colour. To mitigate the risk of mass mortality from these deteriorating conditions, the cultivation lines were relocated in March to an adjacent open backwater system near the sea mouth for the remainder of the grow-out period, with final harvest conducted in June.

Over the total 7 month rearing period, the mussels achieved average shell length growth rate of 8.7 mm per month, reaching a final harvestable shell length of 70.4±9.26 mm and a total weight of 25.49±5.91 g (Fig. 8a, b). The monthly SGR for shell length ranged from 0.04 to 3.87% day⁻¹, establishing a high trial average of 0.93±1.40% day⁻¹. Total mussel production ranged from 11.5 to 18.7 kg m⁻¹, yielding a mean final biomass of 14.9±2.66 kg m⁻¹. Due to space limitations and density dependent crowding on the ropes, the final survival rate at harvest stood at 29.2±5.21%.

Environmental parameters (Fig. 9) varied favourably following the open-water transition. Salinity ranged between 25 and 35 ppt, remaining consistently higher than the Ashtamudi and Vellimon stations due to the close proximity of Neendakara to the bar mouth. Dissolved oxygen levels fluctuated between 4.4 and 5.4 mg l⁻¹, while the pH ranged from 7.4 to 8.2. Water temperature reached a peak of 34.4°C during the March pond phase before stabilising in the open channel. Chlorophyll *a* concentrations averaged 2.4 to 2.7 µg l⁻¹ during the initial pond phase, providing an abundant forage base that supported rapid early growth, while averaging a lower concentration of 0.826 µg l⁻¹ in the open backwater channel.

Vellimon (S3)

The cultivation experiment at the Vellimon station was carried out for 6 months (December 2022 to June 2023) at a stocking density of 1,000 mussels per meter. The initial seed size averaged

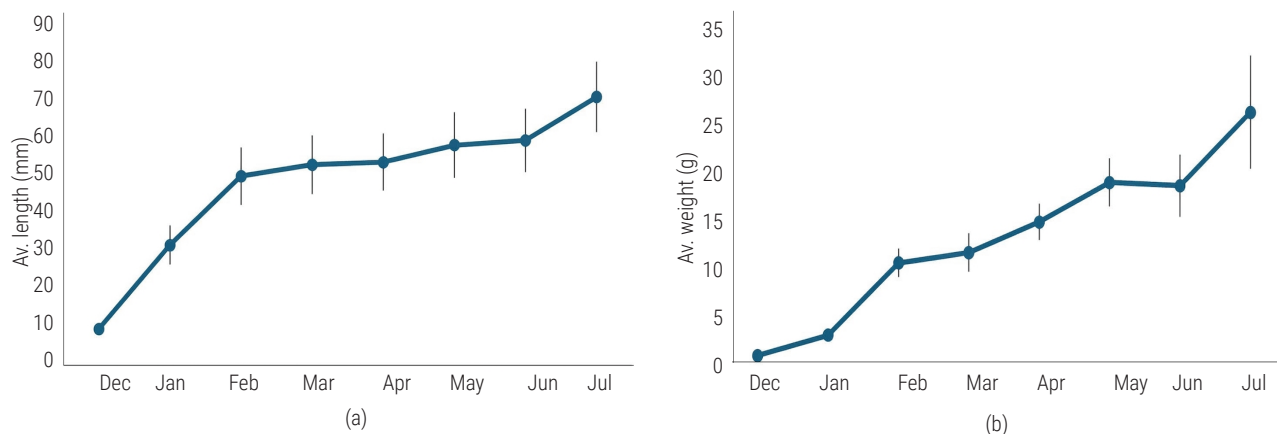


Fig. 8. Growth of mussel in (a) Length (mm) and (b) Weight (g) at Neendakara

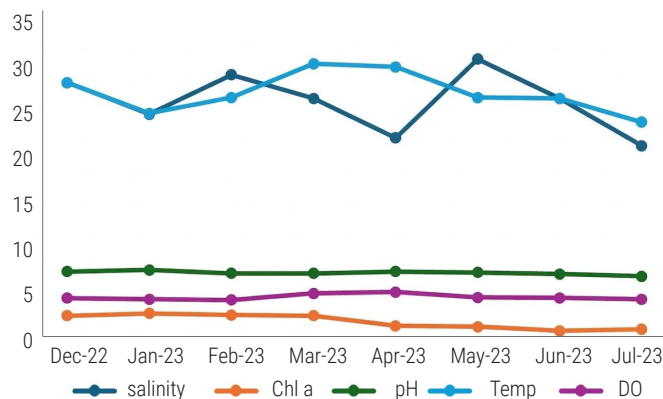


Fig. 9. Monthly variation in water quality at Neendakara

9.5±0.97 mm in shell length and 0.095 ±0.015 g in total weight. The cultivation lines were suspended from the outer framing of a floating raft used concurrently for pearl spot (*E. suratensis*) culture, allowing the mussels to exploit a nutrient enriched, multi-trophic environment. At final harvest, the surviving individuals reached an average shell length of 50.86±7.81mm and a mean total weight of 14.1±3.03 g (Fig. 10a, b).

Hydrographic parameters (Fig. 11) showed distinct seasonal variations. Water temperature ranged from a minimum of 24.2°C in December to a maximum of 31.5°C in March. Salinity values varied between 15 and 27 ppt, while the pH ranged from 7.5 to 8.1. Dissolved oxygen levels fluctuated between 4.1 and 5.2 mg l⁻¹. Chlorophyll a levels at the Vellimon site were moderately high, ranging consistently from 1.42 to 2.29 µg l⁻¹, which supported strong growth performance. Reflecting these favourable environmental conditions, the mussels exhibited a rapid early growth surge, with the monthly specific growth rate peaking at 3.71% day⁻¹ within the first three months of deployment. Over the full 6-month grow-out period, the average monthly growth increment in shell length was 6.9 mm, with the monthly SGR ranging from 0.2 to 3.71 day⁻¹ and establishing a robust trial average of 0.91±1.40% day⁻¹. However, field observations indicated that the final attachment of the mussels on the grow-out lines was highly

sparse and unevenly distributed. Because no protective mesh sleeve netting was wrapped around the cultivation lines at this station, the small, thin-shelled hatchery seed was fully exposed to heavy wild crustacean and finfish predation. Consequently, total production levels were severely limited compared to the other stations, ranging from 1.27 to 3.62 kg m⁻¹, with a mean final yield of only 2.36±1.11 kg m⁻¹. The final survival rate at harvest was heavily reduced by the lack of predator exclusion measures, dropping to a low of 16.79 ±7.87%.

Fig. 12 displays the overall SGR and final survival across the experimental cohorts. At the Ashtamudi station, changing the stocking density from 2,000 to 1,000 seeds m⁻¹ shifted the SGR from 0.54 to 0.94% day⁻¹ and increased final survival from 37.0 to 77.0%. The short term trials at the remaining stations maintained comparable growth rates but lower survival rates. The Neendakara trial (2,000 seeds m⁻¹) reached an SGR of 0.93% day⁻¹ with a final survival of 29%. The lowest final survival was recorded at the unprotected Vellimon site (1,000 seeds m⁻¹) at 16.7%, despite maintaining an SGR of 0.91% day⁻¹.

Discussion

The adoption of hatchery produced green mussel (*P. viridis*) seed represents a significant development for Indian mussel

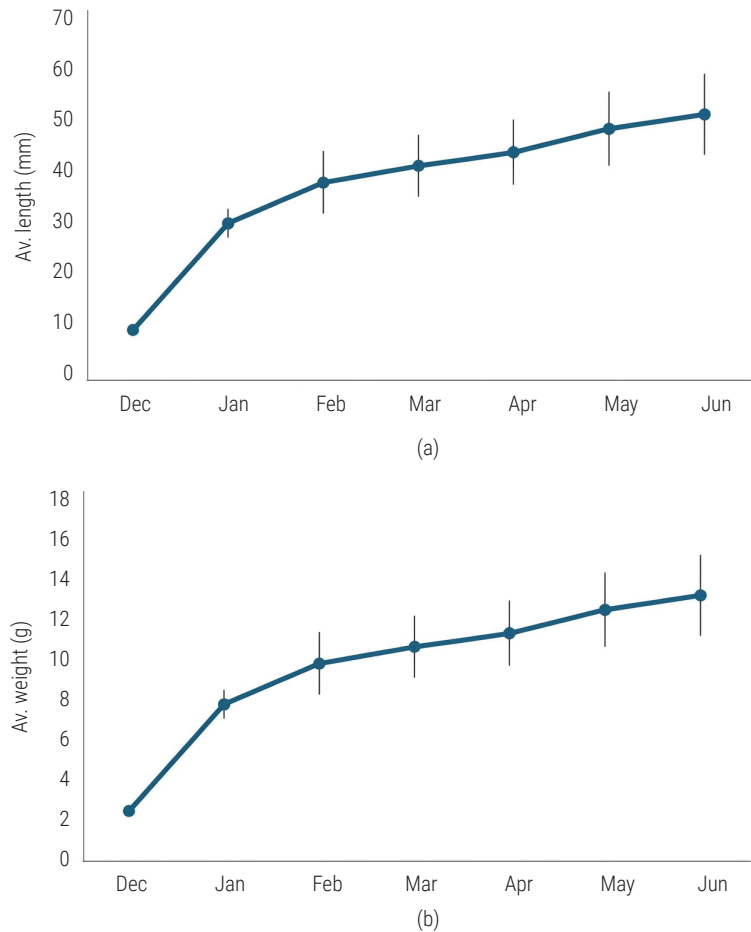


Fig. 10. Growth of mussel in (a) Length (mm) and (b) Weight (g) at Vellimon

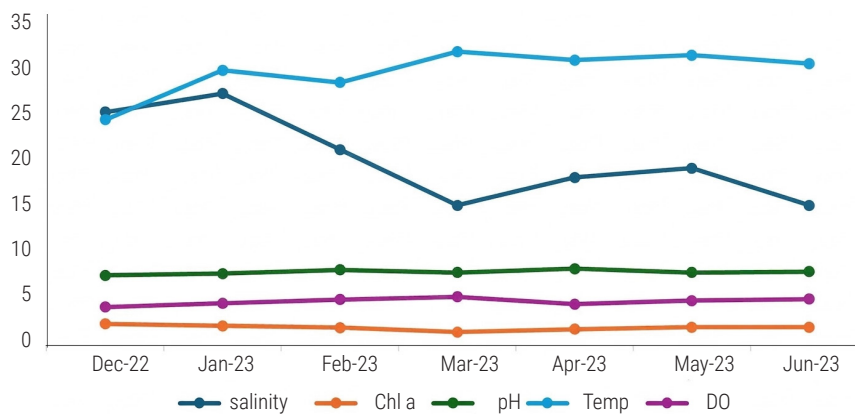


Fig. 11. Monthly variation in water quality at Vellimon

aquaculture. This technology offers a solution to long standing industry problems, including irregular seasonal wild seed supply, fluctuating environmental conditions, and the overharvesting of natural beds. Mussel farming along the south-west coast of India established its foundations in the 1970s. Achari (1975) demonstrated the feasibility of cultivating brown mussels (*P. indica*) at Vizhinjam using

wild seeds attached to bamboo rafts, reporting yields between 6 and 15 kg m⁻¹ over a nine month period. Follow up research by Appukuttan *et al.* (1980) and Kuriakose (1980) confirmed the viability of raft-based systems for both brown and green mussels in Vizhinjam and Calicut using wild seed resources. From 1990 onward, farming expanded significantly, leading to a peak production of approximately

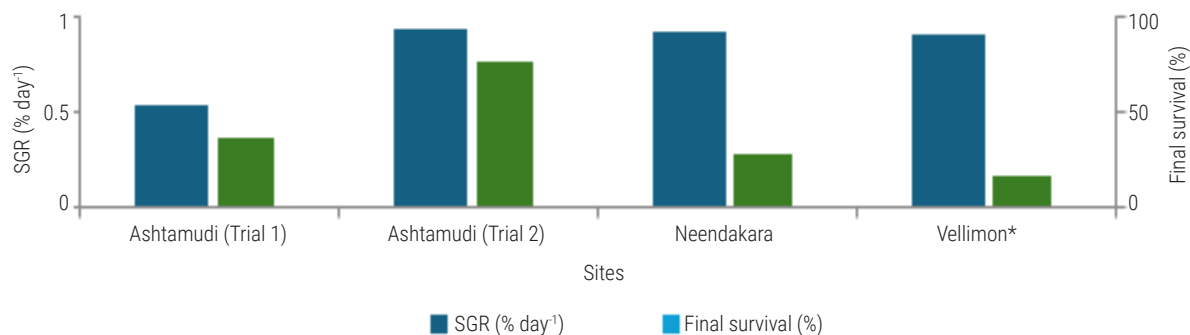


Fig. 12. Comparison of specific growth rate and survival of green mussel at the three sites

18,000 t by 2009. However, annual production subsequently dropped below 500 t by 2016. This decline has been attributed to disease outbreaks, environmental degradation, and a reduction in natural seed availability linked to changing climate patterns (Appukkuttan *et al.*, 2000; Asokan *et al.*, 2001; Kripa and Mohamed, 2008; Geetha *et al.*, 2014; Mohammed *et al.*, 2019; Shinoj *et al.*, 2021). Relying entirely on wild seed collections has restricted the scaling of this sector due to natural environmental variations and unpredictable spatfall. The development of standardised hatchery protocols for *P. viridis* by the Vizhinjam Regional Centre of ICAR-CMFRI (Anil *et al.*, 2022) introduces a reliable alternative. Producing seed in a hatchery, environment provides a year-round supply of uniform quality. More recently, Gomathi *et al.* (2025) conducted sea farming trials along the Kanyakumari coast using hatchery produced seed of the brown mussel *P. indica*, produced at Vizhinjam Hatchery, demonstrating the potential of hatchery based seed supply for sustainable mussel aquaculture.

The field trials carried out in Kollam District provided information on how hatchery produced *P. viridis* seed performs under open environmental conditions. A primary finding of this study is that small hatchery produced spat ranging from 9 to 13 mm in shell length adapt successfully to open grow-out structures, reaching commercial sizes between 51 and 83 mm within 6 to 13 months. This clearly demonstrates that hatchery reared stocks can attain commercially harvestable levels under natural farming conditions, presenting a dependable path for production scaling. At the Ashtamudi site, lines stocked at a density of 2,000 mussels per meter produced an average yield of 33.4 kg m⁻¹ over 13 months, with an average monthly shell length increase of 5.4 mm. Mussels at this location reached a mean shell length of 55.9±6.08 mm during the first six months with monthly shell length increase of 7.2 mm per month. At Neendakara, the mussels grew at a faster average rate of 8.7 mm per month over a seven month period, while growth at Vellimon averaged 6.9 mm per month over six months. These growth rates match or exceed earlier regional records. For instance, Laxmilatha *et al.* (1999) observed a growth rate of 6.8 mm per month over seven months, but their study used larger initial wild seeds averaging 34.4 mm. By comparison, the hatchery seed used in this trial was much smaller, ranging between 9 and 12 mm at stocking. The final shell length of 82.9 mm attained over 13 months at Ashtamudi is consistent with the 83 mm reported by Rajagopal *et al.* (1998) in the Edaiyur backwaters over a 12 month period, even though Ashtamudi exhibited lower ambient chlorophyll concentrations (mean 1.78 µg l⁻¹).

A noteworthy aspect of the early cultivation phase was the high growth rate observed across all stations during the first three months of field deployment. Specific growth rates reached peaks at Ashtamudi (1,000 seeds m⁻¹), Vellimon, and Neendakara. This initial growth surge suggests that the hatchery produced seed undergoes a phase of compensatory growth immediately after transfer to the field. This phenomenon is likely driven by the sudden availability of abundant natural food resources and the removal of spatial or nutritional restrictions inherent to intensive hatchery rearing systems. This capacity for rapid early adaptation highlights the physiological fitness and field readiness of the spat produced, when introduced into open estuarine environments.

When evaluating the full experimental timelines, the data show that the overall SGR values decreased as the culture duration extended. The 13-month Ashtamudi trial (2,000 seeds m⁻¹) recorded the lowest average SGR, even though it yielded the largest overall individuals with a mean shell length of 82.9 mm. This pattern is expected because SGR is a logarithmic calculation. Growth rates naturally decline as mussels increase in body mass, with the majority of structural shell growth occurring during the initial juvenile months. Therefore, the lower average SGR observed in the extended Ashtamudi trial reflects the progressive reduction in relative growth rate that accompanies increasing animal size, rather than indicating poor physiological performance or inferior growth environments. Among the short term, 6 to 7 month grow-out trials, the Neendakara site displayed the most favourable environment for rapid growth, documenting the highest monthly growth rate of 8.7 mm per month, the highest average trial SGR and the largest harvest size at 70.4 mm among the short term treatment cohorts. This high growth performance was maintained despite the physical relocation of the cultivation lines midway through the trial. The high performance at Neendakara is likely explained by the localised hydrographic profile, which was characterised by sustained high salinity levels (25–35 ppt), elevated initial chlorophyll concentrations during the pond phase, and consistent tidal water exchange due to its proximity to the sea mouth.

The position of the cultivation lines at Ashtamudi near finfish cages likely enhanced phytoplankton availability through nutrient runoff from fish feeding. This interaction between bivalve and finfish farming demonstrates the mechanism of integrated multitrophic aquaculture (IMTA), where shared nutrients improve localised productivity (Iglesias *et al.*, 1996; Wong *et al.*, 1999). The trials highlighted a distinction in salinity tolerance across

different growth stages at Ashtamudi. Smaller seeds in the first trial survived low salinity drops down to 10 ppt between May and June, indicating temporary baseline tolerance. In contrast, the second trial at Ashtamudi, which began later in January, suffered heavy mortalities and biomass loss when salinity dropped during the July monsoon. Extending the grow-out period past the standard pre-monsoon window resulted in an average weight loss of 5.22 g alongside increased mortality, confirming that harvest timing is critical. Adjusting the farming calendar to ensure mature mussels are harvested before major monsoonal salinity drops could prevent these seasonal yield losses. Trials initiated during the post-monsoon period at Ashtamudi (January) showed high initial growth kinetics, with SGR ranging between and during the first three months. Rajagopal *et al.* (1998) similarly associated early cultivation success with favourable post-monsoon variables, such as stable salinities and elevated chlorophyll levels.

The outcomes at Neendakara, support the use of adaptive relocation strategies. The stock initially grown inside a tide-fed pond developed well due to stable salinity and high primary productivity. When water quality inside the pond deteriorated during summer due to rising temperatures, shifting the lines into the adjacent open backwater, maintained growth and minimised crop loss. This responsive management strategy resulted in an average yield of 14.9 kg m⁻¹, confirming that flexible site management can stabilise production under changing local conditions (Granada *et al.*, 2016).

The results show that stocking density exerted a more pronounced regulatory effect on final survival metrics than on growth rates. Rearing lines at Ashtamudi and Neendakara utilizing 2,000 mussels per meter resulted in final survival rates of 37 and 29%, respectively. Conversely, reducing the density to 1,000 mussels per meter at Ashtamudi resulted in a higher average survival rate of 77% and an SGR of 0.94% day⁻¹. This lower density allocation produced more than double the survival rate with only a minor variation in individual shell development, indicating that overcrowding primarily manifests as elevated, density dependent mortality rather than severely stunted individual growth. Rajagopal *et al.* (1998) noted that high initial spat densities of 4,000 m⁻¹ dropped continuously over a seven month period due to space constraints, eventually stabilising around 675 mussels/m. Similar patterns have been documented in Galicia, Spain, where lower density allocations consistently produced better growth and survival outcomes (Cubillo *et al.*, 2012). These matching results emphasise that density dependent mortality is a major operational constraint in hatchery seed farming, requiring careful selection of localized stocking limits to maximise total crop biomass.

The use of protective mesh netting was another critical variable affecting survival. Survival rates exceeded 90% during the early grow-out months at Ashtamudi and Neendakara, where protective sleeve nets were deployed. In comparison, at the Vellimon site where no netting was used, survival dropped to an average production was limited to 2.36 kg m⁻¹, despite maintaining a steady average SGR of and a growth increment of 6.9 mm per month. This contrast between steady growth conditions and severe crop loss demonstrates that predator exclusion netting is essential when deploying small hatchery spat under 15 mm in size. Their thin shells leave them highly vulnerable to local predatory finfish and crustaceans, whereas traditional open farming set ups rely on larger wild seeds (20–35 mm) that have already developed thicker, calcified shells. These field observations mirror international bivalve farming

practices in New Zealand and Canada, where predator exclusion netting is standard to ensure high survival rates (Jefferies *et al.*, 1999; Grant and Bacher 2001).

Evaluating growth or survival metrics in isolation can lead to incomplete site assessments. If criteria are restricted to SGR values alone, the Neendakara site appears to be the most optimal environment. However, when growth performance and survival rates are weighed together, the 1,000 seeds m⁻¹ treatment at Ashtamudi emerges as the most balanced and commercially viable management strategy. This configuration combined a high SGR (0.94% day⁻¹), the highest recorded survival rate (77%), and stable volumetric yield, providing a practical baseline for selecting future cultivation parameters.

Local hydrographic conditions, specifically temperature, salinity, and chlorophyll availability exerted strong control over growth rates, consistent with findings from previous coastal bivalve studies in India and elsewhere (Shumway *et al.*, 1985; Ramachandran *et al.*, 2002; Ren *et al.*, 2005; Geetha *et al.*, 2014). Beyond providing stable seed stocks, hatchery systems create opportunities for selective breeding programs aimed at improving growth rates, disease resistance, and stress tolerance, as seen in Australia and Chile (Helm *et al.*, 2004; FAO, 2020). Nursing hatchery seeds to sizes above 20 mm before field deployment in August or September would allow farmers to extend the cultivation window by two to three months. This extension would yield larger mussels at harvest, which command higher prices in commercial markets. Adopting long line set ups, which are widely used in New Zealand and Australia, could improve labour efficiency and expand cultivation into deeper backwaters and open offshore areas. Integrating year round hatchery seed supply with optimised stocking densities and site management offers a pathway to stabilise and scale up marine bivalve production in India.

Present study demonstrated that hatchery produced *P. viridis* seed adapted well to estuarine farming conditions and achieved growth comparable to wild-collected seed. Growth was highest at marine influenced sites, whereas high stocking densities reduced survival due to density dependent mortality. Lower stocking densities improved survival without affecting growth, resulting in better overall crop performance. Protective cover nets and optimal stocking densities reduced early seed losses and improved production. Harvesting should be timed to avoid seasonal salinity declines and post-spawning weight loss. These findings showed that hatchery produced seed can reduce dependence on wild spat and support the sustainable expansion of mussel mariculture along the south-west coast of India.

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