

HIGH-DENSITY NURSERY OF BLACK TIGER SHRIMP *Penaeus monodon* POSTLARVAE AND THEIR PERFORMANCE IN POST-NURSERY PHASE

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Received 25 September 2025; accepted 21 March 2026

ABSTRACT

This study evaluates the effects of nursery stocking density (600 and 1,100 PLs/m²) and nursery duration (3, 4 or 5 weeks) on the performance of black tiger shrimp *Penaeus monodon* postlarvae (PL₁₈) during the nursery phase and the following 4-week post-nursery phase. Results show that survival was high, ranging from 85.1 to 89.6% across all the nursery treatments. Shrimp nursed at 1,100 PLs/m² had a lower growth rate and smaller harvest weight, but better FCR and higher water usage efficiency ($P < 0.05$). Similarly, the longer nursery durations were associated with lower specific growth rate of shrimp but better FCR and higher water usage efficiency ($P < 0.05$). No interactions were found between the two studied factors, nursery density and duration ($P > 0.05$). Survival of shrimp in the post-nursery phase was significantly higher ($P < 0.05$) for shrimp that were nursed for 4 or 5 weeks (73.9 and 83.3%, respectively) compared to those nursed for 3 weeks (62.2%). Furthermore, the size variation of postlarvae that were nursed for 5 weeks was significantly smaller at the end of the post-nursery phase ($P < 0.05$). Overall, the study demonstrated that a combination of higher nursery densities (1,100 PLs/m²) and longer nursery durations (i.e. 5 or 4 weeks) maximized production of the nursery phase and shrimp survival in the post-nursery phase.

Keywords: Advanced nursery, black tiger shrimp, *Penaeus monodon*, high density, nursery duration, post-nursery performance.

Citation: Tung Hoang, Stuart Arnold, Dean Musson, 2026. High-density nursery of black tiger shrimp *Penaeus monodon* postlarvae and their performance in post-nursery phase. *Academia Journal of Biology*, 48(1): 143–153. <https://doi.org/10.15625/2615-9023/23526>

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INTRODUCTION

The black tiger shrimp *Penaeus monodon* is a major species for shrimp farming. Global production of farmed *P. monodon* was 0.7 million tons in 2020 (FAO, 2022) and increased in all the major producing countries such as Vietnam, China, India and Indonesia in recent years (Waiho et al., 2025). For successful grow-out of penaeid species, an advanced nursery phase is highly recommended as it helps improve postlarvae robustness, size, and production efficiencies (Tran et al., 2018; Wormald, 2018). Advanced nursery of *P. monodon* postlarvae was popular in the 1980s and 1990s but was then quickly replaced by stocking PL₁₅₋₁₈ directly into grow-out ponds for convenient management (Rodriguez et al., 1993). It was reported that survival and yield of *P. monodon* were significantly improved when PLs were nursed in a pond for 18 days compared to direct stocking of PLs (Islam & Alam, 2008). However, increasing stocking density in *P. monodon* nursery results in reduced growth and lower survival due to greater cannibalism and degradation of the farming environment (Abdussamad & Thampy, 1994; Pantjara et al., 2021). For advanced nursery, different stocking densities have been experimented with for *P. monodon*, from 72 PLs/m² up to 5,000 PLs/m³ (Arnold et al., 2009; Ali et al., 2021). All these researchers have concluded that shrimp growth and survival are density dependent.

Nursery duration is also an important factor to consider. As shrimp grow, their standing biomass and the amount of waste increase, resulting in more challenges for water quality management and increased mortality by cannibalism (Wasielesky et al., 2013). Advanced nursery periods for *P. monodon* vary from one to six weeks (Pantjara et al., 2024). Extensive pond farmers in Vietnam often nurse *P. monodon* PL₁₅ for 2–3 weeks before stocking (Hoang et al., 2024). We have achieved 80% survival when nursing PL₁₅ of *P. monodon* at 500–600 PLs/m² for four weeks in Australia (Arnold et al., 2021) and have piloted a nursery density of 1,100 PLs/m² with promising results. Nevertheless, it is unknown

how nursery duration may affect shrimp survival and growth.

In this study, we evaluated possible effects of stocking density and nursery duration on the performance of *P. monodon* PL₁₈ and explored whether larger juveniles are more robust in the post-nursery phase. The obtained results are expected to help optimize intensive nursery systems and the growth of the black tiger shrimp *P. monodon*.

MATERIALS AND METHODS

This experiment had two phases: nursery (3–5 weeks) and post-nursery (4 weeks). The nursery phase was designed to evaluate possible effects of two factors: stocking density (600 and 1,100 PLs/m²) and nursery duration (3, 4 and 5 weeks), forming six different treatments. Each treatment had three replicate 2,150-L tanks. Specific-pathogen-free *P. monodon* postlarvae (PL₁₈) were sourced from a commercial hatchery in southeast Queensland and road-transported to the Bribie Island Research Centre. They were acclimated for 30 min at arrival, then randomly selected, counted and released into the experimental tanks. Body wet weight of the postlarvae was 6.33 ± 0.32 mg ($n = 100$) at stocking time. The post-nursery phase was to evaluate if higher nursery density or longer nursery period had any carryover effects on shrimp. Shrimp harvested from each replicate 2,150-L tank in the nursery phase were stocked in two replicate 90-L tanks in the post-nursery system, creating six replicate tanks per treatment. Tank management and animal husbandry were identical for all the experimental tanks in both phases.

In the nursery phase, all the experimental tanks had half their surface area covered with twin walled polygal lids to reduce light intensity and heat loss. Water temperature was maintained with a heat exchanger. The experimental tanks were supplied with 1- μ m filtered and treated (ozone, UV and carbon) seawater, chlorinated at 100 ppm and then aerated for 48 hours. De-chlorination was conducted with sodium thiosulphate if required. *Chaetoceros muelleri* was sourced

from the Australian National Algae Culture Collection (ANACC) and inoculated into the experimental tanks 13 days prior to stocking. To maintain the bloom, SureFlow Aqua (SFA) fertilizer (Elders, Australia) was applied at 5 or 10 g on DOC_{1, 3, 6, 8 and 13} (DOC: day of culture). Sodium metasilicate (5 or 10 g) was applied on DOC_{1, 6 and 13} depending on the SiO₂ and chlorophyll-a levels. The condition of the bloom was assessed daily by monitoring chlorophyll-a concentrations using a ProDSS handheld multi-meter (YSI, USA). Water exchange was conducted on DOC₇ (50%), DOC₅ (50%) and DOC₃ (25%) to thin the bloom. During the first seven days, frozen *Artemia* nauplii was provided initially at 1.15 g/day and increased to 2.1 g/day in tanks stocked at 600 PLs/m² and doubled in tanks stocked at 1,100 PLs/m². Feeding was conducted with a commercial nursery diet (Propel-N, Ridley Aquafeeds) with crumble sizes of 500–700 µm for the first two weeks and 700–1,000 µm for the remainder of the experiment. Shrimp were fed every three hours by automatic belt feeders (FIAP, Fresh by Design, Australia). Feeding rate was initially set at 35% of shrimp biomass per day and then adjusted to 8–13% daily based on feed consumption, water quality and estimated biomass. Uneaten feed was assessed by scooping a dip net along the bottom of the tank. Feed amounts administered were recorded daily for each tank. Water quality parameters were monitored during the entire nursery experiment twice a day at 08:00 and 13:00 for water temperature, pH and chlorophyll-a; and daily at 08:00 for dissolved oxygen, salinity and turbidity using a handheld multiparameter probe (ProDSS, YSI, USA). Water samples were collected twice a week and analysed for ammonia, nitrite and silica using a photometer (9500, YSI, USA). Alkalinity was maintained at 130–155 mg CaCO₃/L. To monitor shrimp growth and adjust the feeding rate, a sample of 50–100 shrimp were randomly collected from each tank and bulk weighed on DOC_{7, 14, 21 and 28} until the termination of the treatments.

The post-nursery phase lasted for four weeks using a flow-through system and

comprised six different treatments. Each treatment had six 90-L replicate tanks (Ø600, H460, SA = 0.28 m²). All tanks were covered with a lid to prevent shrimp from jumping out. A piece of fly screen (30 × 40 cm) was suspended in each tank to provide “shelter” during moulting. The experimental tanks were supplied with 1-µm filtered, ozone sterilised, carbon and UV filtered seawater at 0.7 L/min equivalent to 11.2 complete water exchanges daily. A heat exchange system was used to maintain temperatures above 28 °C. Each tank was equipped with one central air diffuser and one Fish Mate F14 automated fish feeder (Pet Mate, Surrey, England). Three stocking events were conducted, corresponding with the conclusion of each nursery phase at weeks 3, 4 and 5. Each time, 40 shrimp harvested from one replicate tank of a nursery phase’s treatment were randomly selected and acclimated to post-nursery conditions overnight. Early the next day 30 shrimp were randomly selected, blot dried and individually weighed to estimate their average initial weight and stocked into two replicate 90-L tanks at 15 pcs/tank, resulting in a stocking density of circa 53 pcs/m². Thus, there were 6 replicate tanks for each treatment in the post-nursery phase. All treatments were fed the same shrimp pellets, Propel-S (Ø1.0–1.7 mm, L1.7–2.3 mm, made by Ridley AquaFeeds, Australia). Shrimp were fed to 120% satiation five times a day including one manual (09:00) and four auto feeds (13:00, 18:00, 23:00 and 04:00) throughout the experimental period. Uneaten feed was removed daily by siphoning. The amount of uneaten feed was scored and recorded each day. This information was used to adjust the next day’s feed ration. Water temperature (29.1 ± 0.2 °C) and dissolved oxygen (6.0 ± 0.2 mg/L) were maintained at optimal levels across all the treatments. Mortalities, shrimp moults and shrimp numbers were recorded for each tank daily. Shrimp were harvested from each tank after four weeks. They were then individually blot dried and weighed.

For data analysis, the specific growth rate (SGR) was calculated as follows: SGR (%/day)

= $100 \times (\ln FW - \ln IW)/T$, where IW and FW are the initial and final weight (mg) of shrimp inside a time interval - T (days). The feed conversion rate (FCR) was calculated as the amount of feed used/total biomass produced. Size variation of shrimp is estimated as coefficient of variation (CV) of individual body weights. Reduction of size variation during the post-nursery phase is the difference between CV_1 (initial CV at stocking time) and CV_F (CV at the termination of the experiment). Two-way ANOVA was performed using the statistical software SigmaPlot 15.0 (Inpixon, 2022). Important assumptions about normal distribution and homogeneity were all checked for the collected data before analysis (Sokal & Rolf, 1995). Data that did not meet the normality assumption, such as harvest biomass (g/m^2) and CV of body weight (%), were square-root and arcsine transformed, respectively, to obtain normality before being re-analyzed. Where a significant difference was detected at $\alpha = 0.05$, Holme-Šídák post hoc test was used for pairwise multiple comparison.

RESULTS

Effects of nursery density and duration

Water temperature stabilized at around 29 °C (Table 1). DO averaged 6.8–7.1 mg/L

across all the treatments. pH only varied between 7.5 and 8.2. TAN steadily increased in all experimental tanks during the first 16 days (Fig. 1) but then was kept within 4–6 mg/L by regular water exchange. NO_2^- was lower than 1.0 mg/L during the first 13 days across all the treatments. For the remainder of the nursery phase more variation in NO_2^- was observed in the higher nursery density treatments (0.7–6.7 mg/L) compared to the lower nursery density ones (i.e. below 2.0 mg/L). Chlorophyll-a concentration was low during DOC_{4-6} and again DOC_{18-20} coinciding with algal crashes. Turbidity started to increase from DOC_{10} towards the end of the nursery phase in all treatments.

There were no significant differences in water quality parameters reported between the two stocking densities ($P > 0.05$) (Table 2). Similarly, there were no differences in these parameters except turbidity among the three nursery duration treatments ($P > 0.05$). Turbidity was significantly higher in treatments of four and five weeks of nursery duration (i.e. 4.4 and FNU, respectively) compared with the 3-week durations (i.e. 3.2 FNU) ($P < 0.05$). No interaction was found between nursery density and nursery duration on water quality ($P > 0.05$).

Table 1. Water quality during the nursery grouped by nursery density and nursery duration.

Within a row for either nursery duration or density means with a different superscript letter are significantly different at $\alpha = 0.05$

Parameters	Nursery duration (weeks)			Nursery density (PLs/m ²)	
	3	4	5	600	1,100
Water temperature (°C)	28.8 ± 0.1	29.1 ± 0.2	29.2 ± 0.3	29.0 ± 0.2	29.0 ± 0.3
DO (mg/L)	7.1 ± 0.05	7.0 ± 0.06	6.9 ± 0.08	7.0 ± 0.1	7.0 ± 0.1
pH	8.0 ± 0.04	7.9 ± 0.07	7.9 ± 0.07	8.0 ± 0.1	7.9 ± 0.1
TAN (mg/L)	3.3 ± 0.4	3.9 ± 0.8	4.0 ± 0.6	3.4 ± 0.5	4.1 ± 0.7
NO_2^- (mg/L)	1.1 ± 1.2	0.9 ± 0.5	1.8 ± 1.5	0.8 ± 0.5	1.7 ± 1.5
Chlorophyll-a (RFU)	10.6 ± 4.8	10.6 ± 2.8	8.0 ± 1.2	10.2 ± 4.1	9.3 ± 2.5
Turbidity (FNU)	3.2 ± 0.3 ^a	4.4 ± 0.9 ^b	4.8 ± 0.9 ^b	3.8 ± 0.8	4.6 ± 1.1

Stocking density and nursery duration both affected SGR, FCR, harvest weight and harvest biomass ($P < 0.05$), but not shrimp survival or size variation at harvest ($P > 0.05$) (Fig. 2). High survival was consistently observed in all

treatments, ranging from 85.1% to 89.6% (Table 2). FCR ranged from 1.29 to 1.44. Better FCR was achieved at either higher stocking density (i.e. 1.31 at 1,100 PLs/m² compared with 1.39 at 600 PLs/m²) or shorter

nursery durations. FCR steadily increased from 1.30 for the 3-week nursery treatments to 1.36 and 1.38 for the 4-week and 5-week treatments, respectively ($P < 0.05$) (Fig. 2).

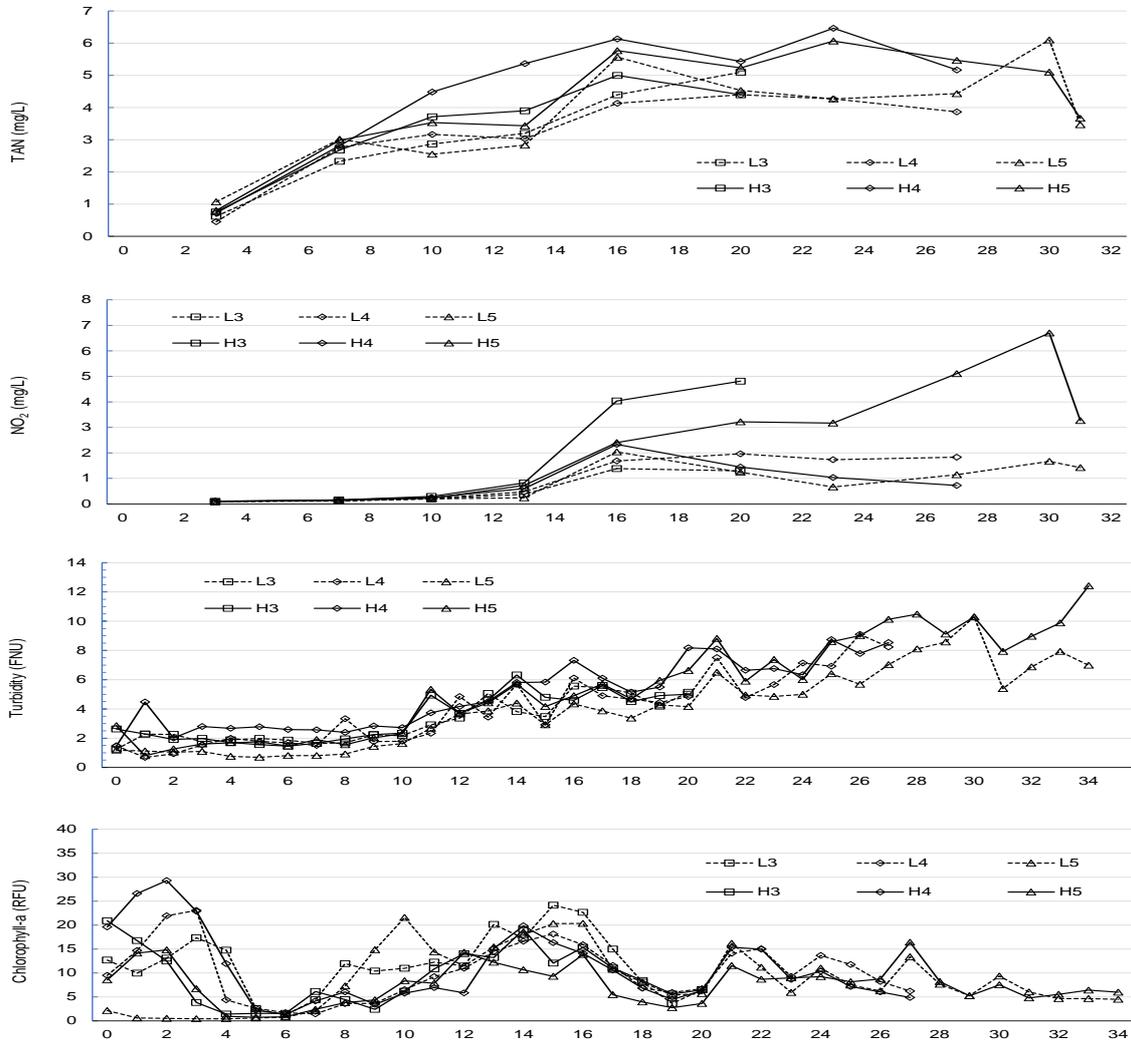


Figure 1. Water quality throughout the nursery phase. Data are treatment means

Table 2. Shrimp performance at different stocking densities and nursery durations

Treatments	Harvest weight (mg)	Harvest biomass (g/m ²)	Survival (%)	SGR (%/day)	FCR
L3	176.6 ± 3.6	94.3 ± 1.8	88.8 ± 0.8	15.8 ± 0.09	1.44 ± 0.02
H3	163.6 ± 1.6	153.3 ± 3.7	85.1 ± 2.1	15.5 ± 0.03	1.29 ± 0.04
L4	432.0 ± 13.9	225.7 ± 11.1	86.8 ± 1.5	15.1 ± 0.12	1.30 ± 0.06
H4	348.3 ± 17.3	344.3 ± 26.4	89.6 ± 2.3	14.3 ± 0.15	1.29 ± 0.08
L5	783.2 ± 36.9	405.8 ± 9.6	86.5 ± 3.7	13.8 ± 0.14	1.41 ± 0.02
H5	643.4 ± 41.2	607.6 ± 64.9	85.3 ± 3.5	13.2 ± 0.17	1.36 ± 0.13

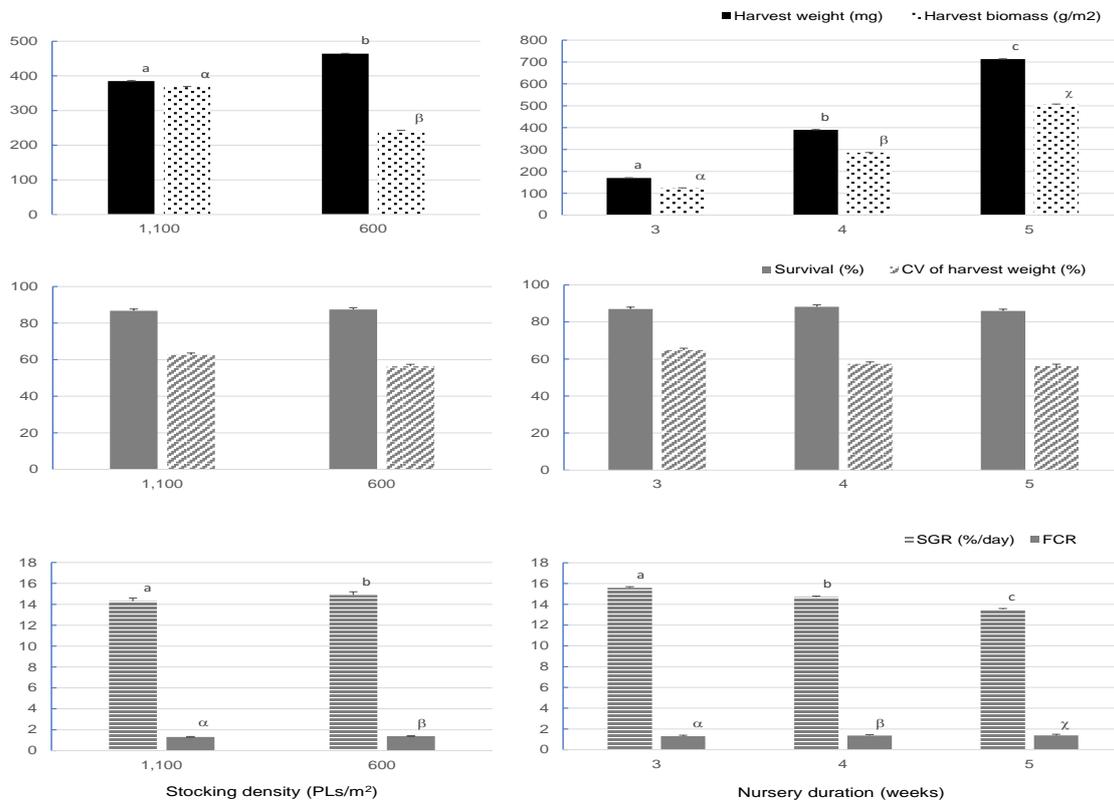


Figure 2. Harvest wet weight (mg/shrimp), harvest biomass (g/m^2), survival (%), CV of harvest weight (%), SGR (%/day) and FCR of the experimental shrimp *Penaeus monodon* at different stocking densities and nursery durations. Means with different characters are significantly different ($P < 0.05$)

Shrimp nursed at the lower stocking density reached significantly larger sizes at harvest, i.e. 20% larger than those nursed at the higher density. Longer nursery durations produced significantly larger juveniles ($P < 0.05$). The average body weight of shrimp after three weeks of nursery was only 170 mg, while that was doubled every week after, i.e. 390 mg and 713 mg after four and five weeks of nursery, respectively (Fig. 2). As a result, harvest biomass was significantly higher ($P < 0.05$) at either higher stocking density or with longer nursery duration. Regardless of nursery duration, the higher stocking density produced a harvest biomass of 368.4 g/m^2 on average or 1.5 fold higher than that of the lower stocking density. Similarly, extending the nursery period from three weeks to four weeks and from three weeks to five weeks produced 2.3 and 4.1 fold higher harvest biomass (Fig. 2).

SGR was significantly lower ($P < 0.05$) when the nursery duration was extended. The highest SGR ($15.3\%/day$) was obtained with a 3-week nursery compared with $14.7\%/day$ and $13.5\%/day$ with a 4-week and 5-week nursery, respectively (Fig. 2). No significant difference in size variation at harvest time ($P > 0.05$) was observed for either stocking density or nursery period. Measured as CV of body weight, size variation at harvest time ranged from 51.1 to 68.0%. The effects of stocking density and nursery duration, where existed, appear to be independent. No significant interaction was detected ($P > 0.05$) between these two factors across all the parameters used for evaluation of shrimp performance.

Nursery density and duration both significantly affected water exchange rate and water usage efficiency (calculated as water

volume in m³ required to produce 1 kg of shrimp at harvest) ($P < 0.05$). The higher nursery density needed more water exchange but was more efficient regarding water usage. The average daily water exchange rate was 9.4%/day for the 1,100 PLs/m² treatments, significantly higher ($P < 0.05$) than that (8.0%/day) for the 600 PLs/m² treatments (Fig. 3). However, the 1,100 PLs/m² treatments required only 8.3 m³ of water to produce one kg of shrimp or 28% lower than the 11.5 m³ required for the 600 PLs/m² treatments.

Longer nursery durations required significantly higher water exchange rates but were significantly more efficient regarding water usage efficiency ($P < 0.05$) (Fig. 3). As nursery duration increased, the average daily water exchange (% of tank volume/day) increased 2.1 and 3.5 folds, for the 4-week and 5-week treatments, respectively. Water usage efficiency exhibited a reverse pattern. The two longer nursery durations (i.e. four and five weeks)

were more efficient, requiring 8.9 and 9.1 m³ of water to produce 1 kg of shrimp, significantly lower ($P < 0.05$) than the 11.7 m³/kg for the 3-week nursery duration.

Significant interactions were found between nursery density and nursery duration, affecting the water exchange rate and water usage efficiency ($P < 0.05$). When nursery duration was three weeks, no difference in water exchange rate was found between the two nursery densities (i.e. 3.8 and 4.0 %/day). However, as nursery duration increased, the higher nursery density treatments required more water exchange than the lower nursery density. Similarly, water usage efficiency improved with higher nursery density and longer nursery duration. The best water usage efficiency (7.7 and 8.0 m³/kg) was obtained in the H5 treatment (1,100 PLs/m² × 5 weeks) and the H4 treatment (1,100 PLs/m² × 4 weeks). The L3 treatment had the poorest water usage efficiency (14.3 m³/kg) among all the treatments ($P < 0.05$) (Fig. 3).

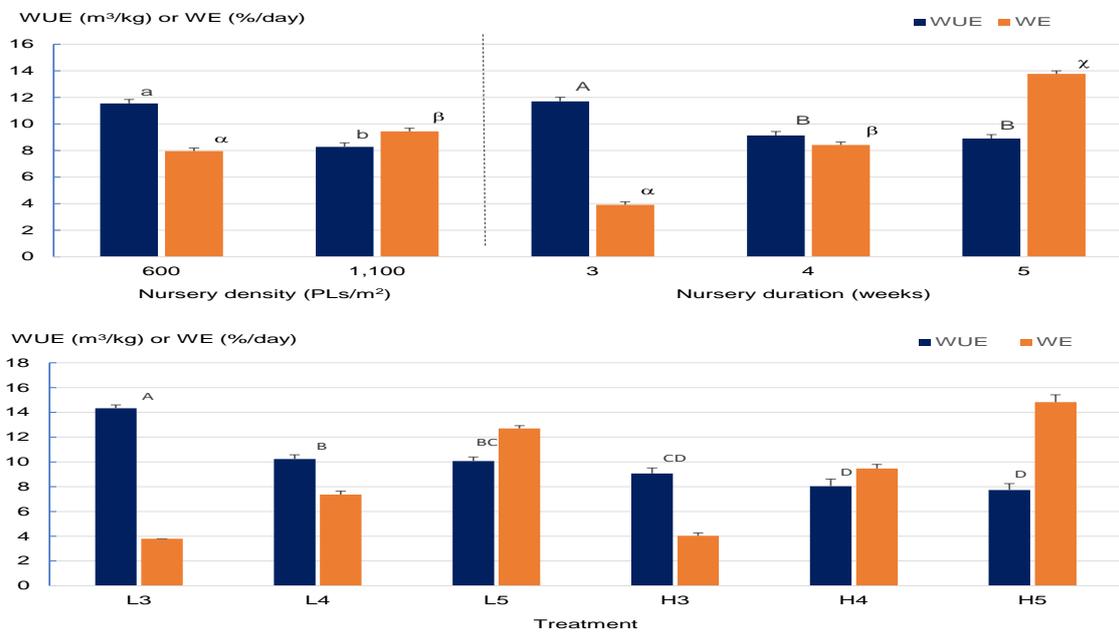


Figure 3. Average daily water exchange rate - WE (%/day) and water usage efficiency (m³ required to produce 1 kg of shrimp at harvest) summarized by nursery density, nursery duration and treatments. Bars with different letters or symbols are significantly different at $\alpha = 0.05$

Shrimp performance in the post-nursery phase

Shrimp grew well in all treatments during the post-nursery phase of four weeks. Survival ranged from 62 to 89% on average across the treatments (Table 3). Nursery density did not

affect shrimp performance in the post-nursery phase ($P > 0.05$), but nursery duration had significant effects on growth, survival, size variation and reduction of size variation ($P < 0.05$) (Table 3). No interactions were detected between these two factors on all the monitored parameters ($P > 0.05$).

Table 3. Shrimp performance in the post-nursery phase

Treatments	Initial weight (mg)	Final weight (mg)	SGR (%/day)	Survival (%)	CV reduction	CV of IW (%)	CV of FW (%)
L3	155 ± 8	1,207 ± 96	7.3 ± 0.3	62.2 ± 5.1	1.5 ± 2.6	65.4 ± 5.7	64.0 ± 6.3
H3	148 ± 17	946 ± 99	6.6 ± 0.2	62.2 ± 4.4	4.3 ± 4.8	59.2 ± 5.1	54.9 ± 1.7
L4	396 ± 20	2,022 ± 153	5.8 ± 0.1	75.6 ± 4.1	1.0 ± 4.7	48.9 ± 5.4	47.9 ± 4.4
H4	462 ± 56	2,178 ± 194	5.6 ± 0.4	72.2 ± 4.0	10.8 ± 3.4	61.7 ± 3.5	50.9 ± 6.1
L5	699 ± 58	3,149 ± 230	5.4 ± 0.3	88.9 ± 5.1	20.0 ± 5.0	61.1 ± 5.5	41.1 ± 3.4
H5	675 ± 71	3,156 ± 244	5.6 ± 0.4	87.8 ± 3.2	14.3 ± 5.8	54.8 ± 6.2	40.4 ± 4.8

A longer nursery duration significantly improved the survival rate of shrimp in the post-nursery phase (Table 4). The highest survival rate (88.3%) was achieved with shrimp that had been nursed for five weeks, followed by those nursed for four weeks (73.9%). Those nursed for 3 weeks had the lowest survival rate (62.2%) in the post-nursery phase. In contrast, the 3-week nursery duration resulted in the highest growth rate of shrimp (7.0%/day as SGR), 22–27% significantly higher ($P < 0.05$) than the other two nursery

durations. There was no significant difference ($P > 0.05$) in the size variation of shrimp among the treatments at the start of the post-nursery phase. However, at the end of the post-nursery phase, shrimp that had been nursed for five weeks had smaller size variation and greater reduction of size variation compared to shrimp that had been nursed for three weeks ($P < 0.05$). Between the 3-week and 4-week nursery treatments no difference was detected regarding size variation or reduction of size variation ($P > 0.05$).

Table 4. Shrimp performance in the 28-day post-nursery summarized by nursery density and nursery duration. Within a row for either nursery density or nursery duration means with different superscript letter are significantly different at $\alpha = 0.05$

Parameters	Nursery density (PLs/m ²)		Nursery duration (week)		
	1,100	600	3	4	5
IW (mg)	429 ± 60	417 ± 57	152 ± 9 ^A	429 ± 30 ^B	687 ± 44 ^C
SGR (%/day)	6.2 ± 0.2	5.9 ± 0.2	7.0 ± 0.2 ^A	5.7 ± 0.2 ^B	5.5 ± 0.2 ^B
Survival (%)	74.1 ± 3.7	75.6 ± 3.3	62.2 ± 3.2 ^A	73.9 ± 2.8 ^B	88.3 ± 2.8 ^C
CV _I (%)	58.5 ± 2.8	58.6 ± 3.4	62.3 ± 3.7	55.3 ± 3.6	57.9 ± 4.1
CV _F (%)	48.7 ± 2.9	51.0 ± 3.5	59.5 ± 3.4 ^A	49.4 ± 3.6 ^{AB}	40.8 ± 2.8 ^B
CV reduction (%)	9.8 ± 2.8	7.5 ± 3.1	2.9 ± 2.6 ^A	5.9 ± 3.1 ^A	17.1 ± 3.7 ^B

DISCUSSION

The results of our study demonstrate that advanced nursery of *P. monodon* postlarvae for 3–5 weeks is possible at densities of 600–1,100

PLs/m², higher than current common practices (BCG 2019). Survival of *P. monodon* postlarvae in our study was high, ranging from 85.1 to 89.6%. More importantly, shrimp growth (13.2–15.8%/day) and FCR (1.3–1.4)

were all at favourable levels, suggesting that a high-density nursery of *P. monodon* should be considered by the shrimp industry to maximize production efficiencies. Our findings in this study are consistent with our preliminary test for the advanced nursery of *P. monodon* in green-water tanks at 500 PLs/m² (Arnold et al., 2021) and other previous studies. Arnold et al. (2006) reported that survival of *P. monodon* postlarvae was around 80% at 1,000–2,000 PLs/m². Similarly, very high survival (91.6–96.8%) was achieved by Pantjara et al. (2024) when nursing postlarvae of *P. monodon* for 32 days at 1,000–1,500 PLs/m² in a recirculation system. Survival was reduced to 81.7% for their highest nursery density of 2,000 PLs/m².

Shrimp growth rate at 1,100 PLs/m² in our study is higher than reported at similar stocking densities by Pantjara et al (2024). These authors used PL₁₂ for their experiment and obtained 0.26 g of juveniles after 30 days of nursery. Our experimental shrimp were 0.38 g after 28 days and 0.64 g after 35 days. This good growth rate together with high survival of the experimental shrimp indicate good maintenance of water quality in our study during the nursery phase. The concentration of TAN and NO₂⁻ were kept within safe ranges for the experimental shrimp (Lin & Chen, 2001; Valencia-Castaneda et al., 2019). Chlorophyll-a concentration peaked and dropped 2–3 times during the nursery phase indicating a few crashes of the diatom bloom, which is quite common in nursery tanks. Our observations show that *P. monodon* postlarvae foraged on the detritus available after a crash of diatoms. It has been known that natural microbial biomass plays an important role in supporting aquatic animals including penaeid shrimp such as *P. monodon*, *Penaeus vannamei* and *Penaeus stylirostris* (Burford et al., 2004; Jin et al., 2023). The decomposed detritus of *Chaetoceros muelleri* observed in our study can be considered as an *in situ* microbial biomass for the experimental shrimp. Further research is needed to confirm their beneficial effects on shrimp growth and, if so, to develop new nursery techniques that

help manage bloom/crash of *C. muelleri* in shrimp nursery systems effectively.

There has been a strong belief among shrimp farmers that high-density nursery or grow-out of *P. monodon* is not viable due to strong cannibalism and retarded growth rate. For these reasons, BCG (2019) strongly recommended that stocking density for nursery and grow-out of *P. monodon* are limited below 200 pcs/m² and 60 pcs/m² respectively, when no substrates are provided. The results of our study suggest that the aforementioned belief should be re-considered. The higher nursery density tested in our study (i.e. 1,100 PLs/m²) appears viable for a commercial nursery since there was no difference in survival and growth of shrimp compared with those nursed at 600 PLs/m². Moreover, this higher nursery density resulted in better FCR, higher water usage efficiency and a larger number of juveniles at harvest. These advantages altogether outweigh a few disadvantages regarding reduced growth rate and smaller harvest size. The difference of SGR and harvest size of shrimp was small, only 0.6%/day and 78.8 mg, respectively between the two nursery densities in our study.

Another important finding of our study is that prolonging the nursery duration made the nursery more productive and beneficial to shrimp survival in a post-nursery phase, which can be considered as the start of a grow-out phase. Longer nursery durations produced larger juveniles at harvest. Shrimp weight was doubled with every additional week of nursery duration. It was only 170 mg at harvest in the 3-week treatments, but was 390 mg and 713 mg, respectively, in the 4-week and 5-week treatments (Fig. 2). It has been known that a short nursery period is better than direct stocking of PL_{12–15}) to unfavourable conditions during the grow-out phase, as larger juveniles are more robust (Browdy et al., 2017; Islam & Alam, 2008; Pantjara et al., 2024). As a result, higher survival can be expected, theoretically increasing productivity. This is evident in the post-nursery phase of our study. Shrimp that were nursed for five weeks had the highest survival rate of 83.3% in the post-nursery phase, significantly higher than that of shrimp

nursed for four weeks (73.9%) and three weeks (62.2%) ($P < 0.05$) (Table 4). In addition, prolonging nursery duration from three to five weeks yielded a larger reduction of size variation in the post-nursery phase. Reduction of CV of body weight increased steadily from 2.9% for shrimp from the 3-week nursery treatments to 5.9% and 17.1% for those from the 4-week and 5-week nursery treatments, respectively. This promises better survival in further farming periods since larger size variation has been known to encourage cannibalism, resulting in poorer survival in *P. monodon* (Nga et al., 2005; Jiang et al., 2021; Pantjara et al., 2021).

CONCLUSION

The results of our study show that black tiger shrimp postlarvae can be nursed at high densities for up to five weeks. Longer nursery duration or larger size at the end of the nursery phase significantly improves survival of shrimp in the post-nursery phase. For successful application in commercial shrimp farms, we recommend a combination of a stocking density of 1,100 PLs/m² and a nursery duration of five weeks. This will help maximize production efficiency of the nursery phase and, more importantly shrimp survival in the post-nursery phase.

Acknowledgements: This study was co-funded by Minh Phu Seafood Corporation (MPSC, Vietnam) and Commonwealth Scientific and Industrial Research Organisation (CSIRO, Australia). The authors would like to thank Mr. Le Van Quang (Chairman and CEO of MPSC), CSIRO Livestock & Aquaculture Research Program and Dr Quyen Banh (CSIRO) for their valuable supports.

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