Sains Malaysiana 54(3)(2025): 629-640
http://doi.org/10.17576/jsm-2025-5403-02

Growth and Nutritional Quality in Giant Freshwater Prawn, *Macrobrachium rosenbergii* through Live Mealworm Feeding with Probiotic Enrichment

(Pertumbuhan dan Kualiti Nutrisi dalam Udang Galah, *Macrobrachium rosenbergii* melalui Pemakanan Ulat Hidup dengan Pengayaan Probiotik)

SASHWINIE MURALI[1], CHAIW-YEE TEOH[1,3,*], WEY-LIM WONG[2,3]

[1]Department of Agricultural and Food Science, Faculty of Science, Universiti Tunku Abdul Rahman, Jalan Universiti, Bandar Barat, 31900 Kampar, Perak, Malaysia
[2]Department of Biological Science, Faculty of Science, Universiti Tunku Abdul Rahman, Jalan Universiti, Bandar Barat, 31900 Kampar, Perak, Malaysia
[3]Centre for Agriculture and Food Research, Universiti Tunku Abdul Rahman, Jalan Universiti, Bandar Barat, 31900 Kampar, Perak, Malaysia

Received: 24 August 2024/Accepted: 26 November 2024

ABSTRACT

To address the gap in sustainable aquaculture, a 17-week feeding trial was conducted to evaluate locally-sourced mealworms, with and without *Bacillus subtilis* probiotic enrichment, as an alternative feed material for giant freshwater prawn (*Macrobrachium rosenbergii*), assessing their effects on growth, feed utilization, and nutritional composition. Five experimental diets were tested: commercial prawn feed (CPF), CPF combined with live mealworm (CPF+MW), mealworm alone (MW), probiotic-enriched mealworm (PMW), and CPF combined with probiotic-enriched mealworm (CPF+PMW). Triplicate groups of 20 prawns were randomly assigned to each diet. Weight gain among the groups ranged from 421.88% to 529.34%, with no significant differences observed ($P > 0.05$). Prawns fed CPF exhibited a significantly higher feed conversion ratio (FCR) (3.72 ± 0.32, $P < 0.05$), indicating less efficient feed utilization and leading to increased production costs. While CPF (45.01%) and MW (52.44%) diets differed significantly in crude protein content, the prawns fed CPF (59.24%) and MW (60.78%) showed similar crude protein levels. These results suggest that live mealworms are a viable alternative to commercial feed for GFP, maintaining growth performance and nutritional quality. Furthermore, combining live mealworms with commercial feed proves to be an effective feeding strategy, though enrichment with *B. subtilis* did not provide additional benefits for prawn growth or FCR.

Keywords: *Bacillus subtilis*; probiotic enrichment; sustainable feed; *Tenebrio molitor*

ABSTRAK

Untuk menangani jurang dalam akuakultur mampan, suatu kajian pemakanan selama 17 minggu telah dijalankan untuk menilai ulat tempatan dengan dan tanpa pengayaan probiotik *Bacillus subtilis* sebagai bahan makanan alternatif untuk udang galah (*Macrobrachium rosenbergii*), dengan menilai kesannya terhadap pertumbuhan, penggunaan makanan dan komposisi nutrisi. Lima diet uji kaji telah diuji: makanan udang komersial (CPF), CPF digabungkan dengan ulat hidup (CPF+MW), ulat sahaja (MW), ulat yang diperkaya dengan probiotik (PMW) dan CPF digabungkan dengan ulat yang diperkaya dengan probiotik (CPF+PMW). Tiga kumpulan udang sebagai peniga sebanyak 20 ekor secara rawak diberikan bagi setiap diet. Keputusan menunjukkan peningkatan berat dalam kalangan kumpulan berbeza antara 421.88% hingga 529.34%, tanpa perbezaan yang signifikan diperhatikan ($P > 0.05$). Udang yang diberi makan CPF menunjukkan nisbah penukaran makanan (FCR) yang lebih tinggi secara signifikan (3.72 ± 0.32, $P < 0.05$), menunjukkan penggunaan makanan yang kurang cekap dan menyebabkan peningkatan kos pengeluaran. Walaupun diet CPF (45.01%) dan MW (52.44%) berbeza dengan ketara dalam kandungan protein kasar, tetapi udang yang diberi CPF (59.24%) dan MW (60.78%) menunjukkan tahap protein kasar yang serupa. Keputusan ini mencadangkan bahawa ulat hidup adalah alternatif yang sesuai untuk makanan komersial bagi GFP, mengekalkan prestasi pertumbuhan dan kualiti nutrisi. Selain itu, menggabungkan ulat hidup dengan makanan komersial terbukti sebagai strategi pemakanan yang berkesan, walaupun pengayaan *B. subtilis* tidak memberikan manfaat tambahan kepada pertumbuhan atau FCR udang.

Keywords: *Bacillus subtilis*; pemakanan mampan; pengayaan probiotik; *Tenebrio molitor*

INTRODUCTION

Macrobrachium rosenbergii, commonly known as the giant freshwater prawn (GFP), is native to Southeast Asia and commands a market price ranging from RM68 to RM90 per kilogram (Pillai et al. 2022). In Malaysia, GFP aquaculture production reached 189.1 metric tonnes, valued at RM15.5 million in 2023 (DOF 2023). Although hatchery technology such as water treatment, recirculating system and flowthrough system for this species has been commercially established since the 1980s, the reliance on live feed during the larval and post-larval stages leads to high feeding costs, significantly hindering large-scale production (Barroso et al. 2014). Feeding costs constitute the primary operational expenses in modern farming systems, and the rapid expansion of the aquaculture industry is partly attributed to the widespread use of aquafeeds (Turchini, Torstensen & Ng 2009). Aquafeeds are aquaculture feeds, formulated to meet the specific nutritional needs of various aquatic species at different life stages, ensuring an optimal balance of essential nutrients for their growth and development (Turchini, Torstensen & Ng 2009). A reduction in feed prices could lead to significant savings for the aquaculture sector (Kim et al. 2015). To ensure the sustainability of aquaculture, it is essential to explore local alternative sources of protein and energy due to the rising costs of conventional feed components (Khanjani et al. 2023; Rana, Siriwardena & Hasan 2009).

Plant-based protein meals and oils have been identified as potential substitutes for fishmeal and fish oil. They come with challenges such as land use concerns, anti-nutritional factors, and deforestation (Sales & Glencross 2011; Sabaté & Soret 2014; Teoh & Ng 2016). Insects have emerged as viable alternatives to fishmeal due to their sustainability and nutritional benefits (Gałęcki et al. 2021; Hua et al. 2019; Murawska et al. 2021; Oonincx et al. 2020; Sharifinia et al. 2023a; Sharifinia et al. 2023b; van Huis & Oonincx 2017), as they efficiently convert food waste, have a short life cycle, and are widely available across various geographic regions (Danks 2006; Rumpold & Schlüter 2013; van Huis 2013).

Food waste significantly impacts global food security, and Malaysia is no exception. Reports show that Malaysians discard approximately 4,046 tonnes of edible food daily, which is enough to provide three meals a day for three million people (Mohideen 2022). Entotechnology utilizes scientific and technical expertise to harness insects' potential for societal benefits in medicine, agriculture, food, and biotechnology. Recent research highlights it as a promising solution for managing organic waste and sustainably producing food for humans, animals, or fish (Hénault-Ethier 2017; López-Almonte et al. 2024). For instance, insects have been shown to effectively reduce fecal coliforms and Salmonella, as well as cut organic waste by 50-75%, depending on the species and type of waste (Chavez & Uchanski 2021). Entotechnology uses various insect species, with mealworms (*Tenebrio molitor*) being particularly efficient for organic waste management and food production due to their ease of production, low resource demands, and minimal labor requirements (Paris et al. 2024; Patel 2019). Nutritionally, mealworms are valued for their high protein and fat content, surpassing that of earthworms (Parolini, Ganzaroli & Bacenetti 2020) and black soldier fly larvae (Barragán-Fonseca et al. 2023).

The nutrient composition of mealworms is affected by factors such as their life stage, environment, substrate, and diet (Finke 2015; Jeong et al. 2022; Khosravi et al. 2018; Siemianowska et al. 2013). In particular, the larvae of the yellow mealworm are among the most commonly farmed insects for food purposes and are capable of breaking down and consuming a variety of agricultural and food industry byproducts (Bordiean et al. 2020). By adjusting their diet and substrate, it is possible to tailor their nutritional content, making mealworms a valuable resource for sustainable feeding practices across various industries (Berezina 2017; Mancini et al. 2019; Oonincx et al. 2015; Ramos-Elorduy et al. 2002).

Probiotic bacteria, especially *Bacillus* strains, are gaining attention as a sustainable aquafeed strategy to reduce antibiotics in aquaculture, offering benefits like disease prevention, improved FCR, growth, and water quality for freshwater fish and crustaceans (Hai 2015; Nathanailides et al. 2021). Various *Bacillus* species have been isolated from the gut of GFP, with *Bacillus subtilis* shown to be a highly effective coloniser in the gut of GFP post-larvae (PL) (Karthik, Bhavan & Manjula 2018; Seenivasan et al. 2012). These beneficial bacteria act on the GFP by altering intestinal microbiota, secreting antibacterial compounds, competing with pathogens for adhesion sites and nutrients, and producing antitoxins (Cruz et al. 2012). Despite these advantages, research on the impact of feeding live mealworms enriched with probiotics to GFP remains limited. This study aims to explore the impact of live mealworm feeding on GFP with a dual focus: assessing both growth performance and feed efficiency, as well as evaluating the nutritional content. Additionally, it will evaluate whether probiotic-enriched mealworms provide further benefits in these parameters.

MATERIALS AND METHODS

Figure 1 presents an overview of the experimental procedure for this study.

CULTURE OF MEALWORM

In this study, mealworms were used as live feed for GFP following a breeding and culturing process adapted from Bordiean et al. (2022). Initially, 2 kg of live mealworms were purchased from a local aquarium shop in Kampar, Perak, Malaysia, and distributed into four plastic containers (30 cm × 15 cm × 5 cm; W × L × H). As the mealworm population is observed to increase, they were then transferred to additional containers of the same

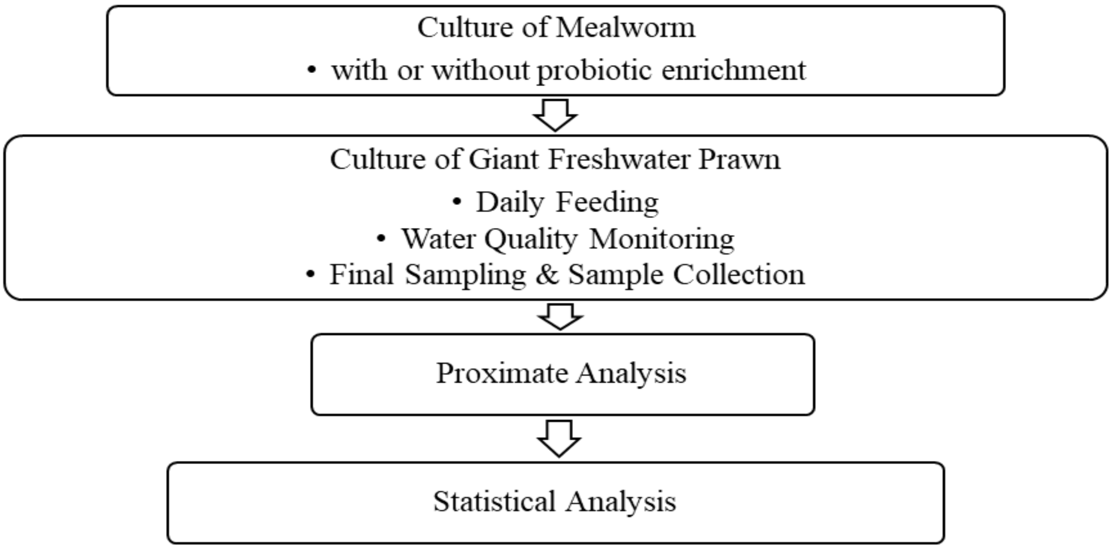

FIGURE 1. Flowchart outlining the experimental procedure for the present study

size to prevent overcrowding, maintaining a density of 1 larva/cm². The mealworms were cultured in a shaded environment with a 12-h light and 12-h dark cycle, with hydration provided through potatoes, carrots, lettuce, and moist cotton pads. Pupae and adult beetles were separated and placed into another container with wheat bran as substrate, along with additional hydration sources, including potatoes, carrots, lettuce, and moist cotton pads. Mealworms of approximately 2 cm in length were harvested, weighed, and used as live feed for the GFP feeding trial. The mealworms were continuously reared until the final week of the GFP feeding trial.

PROBIOTIC ENRICHMENT OF MEALWORM

Probiotic enrichment was performed following a modified protocol from Dadvar et al. (2023). A commercial probiotic, IG Guard A, was obtained from ADBIOTECH Co., Ltd. The probiotic powder contained 2.0 × 10^{10} CFU/kg of *Bacillus subtilis*, 120 g/kg of egg powder, and carrier distillers dried grains (wheat flour and corn flour) up to a total weight of 1 kg. Mealworms, each weighing approximately 154 ± 0.5 mg, were selected for *B. subtilis* enrichment. They were first starved for two days, then placed in a plastic container (1.73 cm × 1.18 cm × 0.56 cm) and given 10 g of IG Guard A. The mealworms were kept in the container for three hours, during which their feeding behavior was monitored to ensure they consumed the probiotic powder. The mealworms were then left in the container for an additional 24 hours to allow for complete intake of the probiotic (Chung et al. 2013), after which they were harvested and used as feed for the GFP feeding trial following the specified feeding regime.

CULTURE OF GIANT FRESHWATER PRAWN

Post-larvae day 15 (PL_{15}) of GFP were sourced from Pusat Penetasan Udang Galah (PPUG) in Kg. Acheh, Malaysia and were acclimated for seven days upon their arrival at the Aquaculture Facilities, UTAR. During acclimation, the PLs were fed twice daily with a commercial prawn diet (Dindings Freshwater Prawn Feed 2203) until satiation. At the start, groups of 20 PLs, each with an initial body weight of 0.44 g ± 0.00, were randomly assigned to each of the 15 tanks (45.72 cm W × 76.20 cm L × 45.72 cm H). The tanks, equipped with a recirculating freshwater system, contained 20 PVC pipes (25 mm diameter × 45 mm length) at the bottom to offer refuge for the PLs (Chong, Teoh & Wong 2022). Five experimental dietary treatments were used in the feeding trial: (1) commercial prawn feed (CPF, control), (2) commercial prawn feed with live mealworms (CPF+MW), (3) live mealworms alone (MW), (4) live mealworms enriched with probiotics (PMW), and (5) commercial prawn feed with probiotic-enriched mealworms (CPF+PMW). The CPF+MW and CPF+PMW diets were prepared in a 1:1 ratio, with 1 g of commercial feed to 1 g of mealworms or probiotic-enriched mealworms, respectively. All experimental diets were weighed on a wet-weight basis and converted to dry weight for calculating the FCR. Each diet was randomly assigned to triplicate groups of prawns. The PLs were fed three times daily at 09:00, 13:00, and 17:00 h to apparent satiation (approximately 15% of body weight per day) (Ng et al. 2017) during the initial weeks, and then twice daily at 09:00 and 17:00 h (approximately 8% of body weight per day) starting from week four (Ng et al. 2017). All PL were batch-weighed weekly to monitor growth performance. The feeding trial was conducted for 17 weeks, with total feed consumption recorded daily. After the 17-week feeding trial, the PL had grown to approximately 10 cm in length and was henceforth referred to as prawn. A final sampling was conducted to measure body weight and collect various samples. The final body weight of all prawns was recorded, and five prawns from each replicate tank were euthanized and stored in a freezer at -20 °C for subsequent analysis of whole-body proximate composition. Prawn growth performance was assessed by measuring the percentage of weight gain. Additionally, the survival rate of the prawns was calculated. Feed intake and FCR were also determined. These parameters were evaluated using the following formulae:

$$\text{Weight gain (\%)} = \frac{\text{final body weight-initial body weight (g)}}{\text{initial body weight (g)}} \times 100$$

$$\text{Survival rate (\%)} = \frac{\text{final prawn number}}{\text{initial prawn number}} \times 100$$

$$\text{FCR} = \frac{\text{total dry feed (g)}}{\text{wet weight gain (g)}} \times 100$$

The total production cost for each treatment was recorded to evaluate the feasibility of using live mealworms, including those enriched with probiotics, in commercial GFP farming.

WATER QUALITY MONITORING

Throughout the 17-week feeding trial, water pH and dissolved oxygen were monitored daily. using a digital pH tester (Extech Instruments, Taiwan) and an Eutech Basic Portable DO Meter DO 6+ (Thermo Scientific, Singapore), respectively. Additionally, water hardness, ammonia (NH_3), nitrite (NO_2^-), and nitrate (NO_3^-) levels were measured weekly using the Freshwater Master Test Kit (API®, USA). To maintain optimal water quality, a weekly water change was carried out, with 70% of the water being replaced in each tank to stabilize pH levels between 7.0 and 8.0 and hardness between 30 and 100 mg/L. If water hardness dropped below the desired range, calcium chloride was added to restore it.

PROXIMATE ANALYSIS

Proximate analysis of the treatment diets and prawn whole-body samples was conducted following standard AOAC methods (AOAC 1997) with modifications as outlined by Teoh and Loo (2022). In summary, dry matter content was determined using the oven-drying method, where samples were dried at 103 °C until a constant weight was achieved. Crude protein (CP) was determined using the Kjeldahl method, which involved digesting the sample with concentrated H_2SO_4 and a catalyst, followed by distillation with water and 32% NaOH. The resulting distillate was titrated with 0.1 N HCl, and the volume of HCl used was recorded. Ash content was determined by incinerating the samples in a furnace at 550 °C for 5 h. For crude fibre analysis, pre-dried, defatted samples were sequentially digested by boiling with 0.13 M H_2SO_4 and 0.23 M NaOH, followed by washing with distilled water using a Fibrebag system for filtration. The digested samples were then ashed at 550 °C for 4 hours and weighed. Crude lipid (CL) was extracted using a modified Folch, Lees and Sloane Stanley (1957) method, where weighed samples were soaked overnight in a chloroform/methanol solution (2:1), homogenized, filtered, and emulsified with distilled water, allowing it to separate into two distinct layers: An upper water-rich layer and a lower lipid-rich chloroform layer. The CL was collected and dried at 40 °C until a constant weight was achieved. Finally, the nitrogen-free extract (NFE) was calculated after the proximate analysis using the formula: NFE = % dry matter – (% ash + % CP + % CL + % crude fiber) (Teoh & Loo 2022).

STATISTICAL ANALYSIS

All data (growth, survival rate, FCR, and proximate composition) were checked for normality using the Shapiro-Wilk test and then analyzed using one-way ANOVA in SPSS 20.0 (SPSS Inc., Chicago, IL, USA). When significant differences were detected, post hoc Duncan's Multiple Range Test was applied for mean comparisons between treatments. All of the statistical probability values were considered significant at $P < 0.05$, and the results are presented as mean ± standard error.

RESULTS AND DISCUSSION

GROWTH PERFORMANCE AND SURVIVAL OF PRAWN

After the 17-week feeding trial, the prawns exhibited weight gain ranging from 421.88% to 529.34% (Table 1), with no significant differences observed among the treatment groups ($P > 0.05$). Prawns fed with CPF+PMW and CPF+MW showed weight gains of 529.34% ± 54.37 and 478.84% ± 28.42, respectively, indicating that a combined diet of CPF and live mealworms could serve as a feeding strategy to reduce reliance on aquafeeds. The addition of probiotics may further enhance growth performance. Choi et al. (2018) found that replacing 50% of dietary fishmeal with mealworms optimally promoted shrimp growth without adverse effects. The use of live mealworms in the present study may account for the differing results compared to studies that used mealworm meal. In another study where the bacterial strain is directly fed, Kolanchinathan et al. (2017) reported growth improvements in tiger shrimp after a 15-day feeding period with live cells of *Bacillus firmus* at a concentration of 3.01×10^9 CFU/g. The administration of probiotics, particularly *Bacillus* spp., has been suggested to enhance growth and immune function in cultured species by secreting lipase, which stimulates the production of essential fatty acids (El-Dakar & Goher 2004; Gullian, Thompson & Rodriguez 2004). However, when the prawns were indirectly administered the bacterial strain, the lack of significant differences among treatments in this study was observed. This outcome is likely due to reduced bacterial delivery and uptake through indirect administration, leading to suboptimal colonization and immune interaction (Hoseinifar et al. 2024). Lower bacterial concentrations, environmental factors like waterborne dispersion, and reduced bacterial adhesion to the prawn's gut may have limited the probiotic effects, resulting in minimal differences among treatment groups (El-Saadony et al. 2022; Kulkarni et al. 2021). In addition, the survival rate of the experimental prawns ranged from 75.00% to 85.00% (Table 1), with relatively higher survival observed in prawns fed live mealworms, regardless of probiotic enrichment. Mortality was primarily attributed to aggressive and cannibalistic behavior. Due to their territorial nature, GFP often attack each other, especially targeting prawns that have just molted, resulting in injuries that frequently lead to death (Seidel, Schaefer & Donaldson 2007). This suggests that partially replacing CPF with live mealworms, whether probiotic-enriched or not, does not compromise and may even enhance the growth and survival performance of GFP.

WATER PARAMETERS OF EXPERIMENTAL TANKS

NO$_2^-$ was not detected in all the tanks and there were no significant differences observed for DO, pH, NH$_3$ levels among the experimental tanks throughout the feeding trial (Table 2). The DO ranged from 7.34 - 7.45 mg/L and pH ranged from 7.39 to 7.44. The lowest NH$_3$ level (0.33 mg/L) was recorded in CPF+PMW tanks while the highest (0.50 mg/L) was detected in CPF, CPF+MW and MW tanks. This result suggests that probiotic enrichment could help to maintain a low NH$_3$ level in the culture tanks. Low NH$_3$ levels are crucial in prawn tanks, as prawns are highly susceptible to ammonia toxicity, which can damage gills, weaken immunity, and increase mortality (Lin et al. 2022). High ammonia disrupts water quality, harms beneficial bacteria essential for waste breakdown, and triggers stress responses that hinder growth and molting (Romano & Zeng 2013). Maintaining low NH$_3$ supports a healthy tank environment, optimizes growth, and reduces the need for frequent water changes or chemical treatments, lowering operational costs. According to Kewcharoen and Srisapoome (2019), adding *B. subtilis* with a concentration of $1 \times 10^3 – 1 \times 10^5$ CFU/mL to water culturing whiteleg shrimp could reduce the total NH$_3$ content, and feeding the shrimp with Artemia enriched with microencapsulated *B. subtilis* (10^9 CFU/g) also decreased the concentration of NH$_3$ and NO$_2^-$ in the culture water (Nimrat et al. 2012). Furthermore, NO$_3^-$ level was significantly higher in the CPF tank (26.67 ± 6.07 mg/L) potentially due to nutrient leaching of the CPF and relatively more feces produced by prawns fed with CPF. Algae growth was observed in CPF tanks, which can disrupt the microbiome balance and lead to mortality due to asphyxiation (Irungu et al. 2018), which partly explain the relatively lower survival rate in those fed with CPF.

FEED CONVERSION RATIO

FCR is crucial in aquaculture as it measures feed utilization efficiency, directly affecting production costs and sustainability. A lower FCR indicates less feed is needed for growth, enhancing profitability and reducing waste (Besson et al. 2016). In this study, prawns fed with CPF had significantly ($P < 0.05$) higher FCR values (3.72 ± 0.32) compared to those on the other diets (Table 1). However, no significant differences in FCR were observed among prawns fed the other four diets ($P > 0.05$). Although the FCR values for prawns fed CPF+MW and CPF+PMW were slightly higher than those for prawns fed MW and PMW, all FCR values remained within the normal range of 1.8 to 3.1, as suggested by Paul and Rahman (2016).

TABLE 1. Growth performance, survival, total feed intake and feed conversion ratio of the experimental prawns after 17 weeks of feeding trial. Values are presented as mean ± standard error of triplicate groups of experimental prawns. Different superscripts in the same row indicate significant differences by the test of $p < 0.05$ using Duncan's multiple range test

Feeding materials[1]	CPF	CPF+MW	MW	PMW	CPF+PMW
Total weight gain (%)	517.52 ± 65.58	478.84 ± 28.42	505.06 ± 84.14	421.88 ± 6.07	529.34 ± 54.37
Survival (%)	75.00 ± 2.89	85.00 ± 5.77	78.33 ± 4.41	81.67 ± 1.67	80.00 ± 2.89
Total feed consumption (g) (ww)[2]	129.87 ± 2.21^{ab}	124.67 ± 3.47^{a}	161.77 ± 9.53^{c}	150.90 ± 3.31^{bc}	127.71 ± 6.20^{ab}
Total feed consumption (g) (dw)[3]	117.02 ± 1.99^{c}	75.74 ± 2.10^{b}	50.78 ± 2.99^{a}	47.37 ± 1.04^{a}	77.58 ± 3.77^{b}
FCR	3.72 ± 0.32^{b}	2.19 ± 0.01^{a}	1.63 ± 0.31^{a}	1.63 ± 0.40^{a}	2.24 ± 0.32^{a}

[1] Feeding materials: CPF = commercial prawn pellet (control); CPF+MW = commercial prawn pellet + mealworm; MW = mealworm; PMW = probiotic mealworm; CPF+PMW = commercial prawn pellet + probiotic mealworm

[2] Total feed consumption was calculated in wet weight (ww)

[3] Total feed consumption was calculated in dry weight (dw)

The results were influenced by the prawns' feeding preferences, with a tendency to favour mealworms over commercial feed in the CPF+MW and CPF+PMW groups. The highest feed consumption in wet weight was recorded in prawns fed with MW. This preference aligns with the natural diet of wild prawns, which includes mollusks, oligochaetes, insects, and other crustaceans (Chakraborty 2017). Such inherent feeding behaviors, including capture and consumption methods, may significantly influence FCR by affecting feed utilization efficiency (Ahmed, Lodhi & Shukla 2021). In a study by Motte et al. (2019), replacing 50% of dietary fishmeal with mealworm meal improved the FCR of whiteleg shrimp from 1.59 to 1.20. Although previous research shows that direct probiotic supplementation improves prawn FCR (Kolanchinathan et al. 2022; Zokaeifar et al. 2012) and suggests that multiple probiotic strains enhance FCR and growth in penaeid shrimp, limited studies have explored their effects on *Macrobrachium* spp. (Toledo et al. 2019). In this study, probiotic enrichment of mealworms did not significantly impact prawn FCR, suggesting that the supplementation method may not have been optimal. Future research could examine higher probiotic concentrations, strain combinations, and extended feeding periods to optimize FCR and growth performance in GFP.

PROXIMATE COMPOSITION OF EXPERIMENTAL FEED MATERIAL

Significant differences were observed in the dry matter, ash, crude fiber, CP, and CL contents among the experimental feed materials used in this study (Table 3). The CPF had the lowest CP (45.01% ± 0.48) and CL (14.62% ± 0.17) contents, while MW showed the highest values, with CP at 52.44% ± 0.19 and CL at 31.55% ± 0.59. PMW exhibited a similar CL content to MW. The nutritional composition of mealworms is reflective of their food source; mealworms fed wheat bran displayed higher CP levels compared to those fed rye bran (Bordiean et al. 2022). Importantly, the type of dietary protein source often holds more significance than its quantity (Rumbos et al. 2020). In this study, while the CP concentrations differed between MW (52.44% ± 0.19) and PMW (49.63% ± 0.52), both diets maintained similarly high CL contents (31.55% ± 0.59 and 32.50% ± 0.33, respectively), which were significantly higher than the other three diets. This suggests that the CL content in mealworms remains consistent even with probiotic enrichment. Dreassi et al. (2017) also found that feeding mealworms different food, such as wheat bran, rye bran, and rapeseed meal, resulted in similar CL content in the larvae. The ash content was approximately 9.28% ± 0.42 – 9.67% ± 0.62 in CPF+MW, MW, and PMW, while CPF had the highest ash percentage at 14.70% ± 1.78. Ash content in the feed represents inorganic compounds like calcium, essential for prawn shell formation during molting. Sufficient calcium ensures prawns receive the nutrients needed for successful molting and healthy growth (Khalid et al. 2023). Additionally, CPF+PMW had the highest crude fiber percentage (7.04% ± 0.67) among the five feed treatments.

PROXIMATE COMPOSITION OF PRAWN

The ash content (3.32–4.87%) and crude fiber (7.03–8.91%) were not significantly different across the experimental prawns (Table 3). However, prawns fed with CPF+MW exhibited the lowest dry matter content (20.36% ± 4.83), which was significantly lower than that in prawns fed with CPF+PMW (26.96% ± 3.72; $P < 0.05$). The dry matter content in prawns fed with CPF, MW, and PMW showed no significant differences (22.09% ± 0.96, 22.27% ± 2.79, and 21.17% ± 1.71, respectively). Notably, prawns fed with MW (60.78% ± 1.05) and CPF (59.24% ± 1.98) had significantly higher CP content. Interestingly, despite CPF having the lowest CP among the diets, prawns fed with CPF showed relatively high CP content in their bodies. A commercial feed specifically formulated to meet the nutritional requirements of prawns, including all ten essential amino acids (EAAs) such as methionine and lysine, which are deficient in mealworms (Nunes et al. 2014). Although mealworms lack methionine, supplementation of this EAA is only necessary when dietary protein levels

TABLE 2. Water parameters of experimental tanks throughout the feeding trial. Values are presented as mean ± standard error of triplicates groups of experimental prawns. Different superscripts in the same row indicate significant differences by the test of $p < 0.05$ using Duncan's multiple range test

Feeding materials[1]	CPF	CPF+MW	MW	PMW	CPF+PMW
DO (mg/L)	7.45 ± 0.45	7.43 ± 0.04	7.37 ± 0.05	7.35 ± 0.04	7.34 ± 0.02
pH	7.44 ± 0.08	7.42 ± 0.07	7.43 ± 0.03	7.39 ± 0.03	7.43 ± 0.05
Ammonia (mg/L)	0.50 ± 0.00	0.50 ± 0.00	0.50 ± 0.00	0.42 ± 0.08	0.33 ± 0.08
Nitrite (mg/L)	0.00	0.00	0.00	0.00	ND
Nitrate (mg/L)	26.67 ± 6.07^b	10.00 ± 0.00^a	5.00 ± 0.00^a	6.67 ± 1.67^a	10.00 ± 0.00^a

[1] Feeding materials: CPF = commercial prawn pellet (control); CPF+MW = commercial prawn pellet + mealworm; MW = mealworm; PMW = probiotic mealworm; CPF+PMW = Commercial prawn pellet + probiotic mealworm

fall below 20–30% (Motte et al. 2019). Specifically, GFP requires all ten EAAs, though their precise proportions remain unclear (Sarman et al. 2018). Furthermore, the highest CL content was observed in prawns fed with CPF (14.19% ± 3.58), which was significantly higher than those fed with MW (7.90% ± 4.76), PMW (6.89% ± 1.54), and CPF+MW (3.99% ± 0.55), but not significantly different from those fed with CPF+PMW (11.09% ± 2.22). The CL content in prawns did not correspond to that of the experimental diets (MW, PMW, and CPF+MW), indicating that the dietary fatty acid composition may influence CL digestibility in prawns (Glencross et al. 2002). This inconsistency may stem from selective absorption or metabolism of specific fatty acids influenced by the prawn's physiological needs (Kumar et al. 2018). Studies show that prawns may preferentially retain certain lipids to maintain membrane fluidity, support growth, or adapt to stress (Tocher & Glencross 2015). Additionally, interactions between dietary lipids and digestive enzymes affect fatty acid absorption (Xie et al. 2020), and species-specific metabolic pathways may adapt to different lipid sources (Chen et al. 2015; Ding et al. 2022). Additionally, a previous study on tiger shrimp demonstrated that dietary phospholipids could significantly enhance CL digestibility and emulsification of neutral lipids (Glencross, Smith & Williams 1998). It is suggested that adding dietary phospholipids could improve CL digestibility in prawns, enhancing lipid metabolism, nutrient absorption, and growth. Future research on this approach may optimize prawn diets, improving feed utilization efficiency and supporting sustainable aquaculture.

EXPERIMENTAL FEED PRODUCTION COST

In this study, PMW feed was the most expensive at RM53.09 per kg, followed by mixed feeds of CPF+PMW at RM23.26 per kg and CPF+MW at RM6.34 per kg (Table 4). Panini et al. (2017) highlighted the high initial cost of mealworms compared to commercial prawn feeds but noted that large-scale mealworm farming could reduce costs over time. Grau, Vilcinskas and Joop (2017) supported this, showing that economies of scale and the use of organic waste as feed make mealworm production more viable as scale increases. Though costly for small-scale prawn farms, mealworm farming has sustainability benefits, converting waste into high-protein feed and reducing environmental impact (Colombo et al. 2023; Oonincx et al. 2015). On-site mealworm production can cut transportation costs and carbon emissions, offering a sustainable feed option for aquaculture (Rumbos et al. 2020).

TABLE 3. Proximate composition of experimental feed materials and the prawns after 17 weeks of feeding trial. Values are presented as mean ± standard error of triplicate of samples. Different superscripts in the same row indicate significant differences by the test of $p < 0.05$ *using Duncan's multiple range test*

Feeding materials[1]	CPF	CPF+MW	MW	PMW	CPF+PMW
			Feed		
Dry matter (%)	90.11 ± 0.47^{e}	57.99 ± 0.33^{c}	32.24 ± 0.43^{a}	41.26 ± 1.24^{b}	64.62 ± 1.16^{d}
Ash (%)	14.70 ± 1.78^{b}	9.67 ± 0.62^{a}	9.28 ± 0.42^{a}	9.38 ± 0.35^{a}	12.57 ± 1.36^{ab}
Fibre (%)	2.27 ± 0.30^{a}	3.32 ± 0.12^{a}	4.03 ± 0.72^{a}	2.70 ± 0.63^{a}	7.04 ± 0.67^{b}
Crude protein (%)	45.01 ± 0.48^{a}	47.01 ± 0.24^{b}	52.44 ± 0.19^{d}	49.63 ± 0.52^{c}	47.44 ± 0.70^{b}
Lipid (%)	14.62 ± 0.17^{a}	27.29 ± 2.39^{c}	31.55 ± 0.59^{d}	32.50 ± 0.33^{d}	19.78 ± 0.21^{b}
NFE[2] (%)	23.40	12.71	2.70	5.79	13.17
			Prawn		
Dry matter (%)	22.09 ± 0.96^{ab}	20.36 ± 4.83^{a}	22.27 ± 2.79^{ab}	21.17 ± 1.71^{ab}	26.96 ± 3.72^{b}
Ash (%)	4.97 ± 0.94	3.32 ± 1.01	3.57 ± 0.92	3.84 ± 1.52	4.67 ± 1.46
Fibre (%)	7.03 ± 1.28	7.93 ± 1.70	7.79 ± 1.30	8.21 ± 1.40	8.91 ± 3.00
Crude protein (%)	59.24 ± 1.98^{b}	48.93 ± 1.75^{a}	60.78 ± 1.05^{b}	50.40 ± 1.25^{a}	50.12 ± 1.28^{a}
Lipid (%)	14.19 ± 3.58^{c}	3.99 ± 0.55^{a}	7.90 ± 4.76^{ab}	6.89 ± 1.54^{ab}	11.09 ± 2.22^{bc}
NFE[3] (%)	14.57	35.83	19.96	30.66	25.21

[1] Feeding materials: CPF = commercial prawn pellet (control); CPF+MW = commercial prawn pellet + mealworm; MW = mealworm; PMW = probiotic mealworm; CPF+PMW = Commercial prawn pellet + probiotic mealworm

2Nitrogen free extract (NFE) = 100 – (crude protein + crude lipid + crude fibre + ash)

TABLE 4. Cost (RM/kg) of experimental feed for giant freshwater prawn[1]

Feeding materials[2]	CPF	CPF+MW	MW	PMW	CPF+PMW
Component					
Mealworm[3]	Nil	5.30	13.75	12.83	5.43
Wheat bran[4]	Nil	0.42	1.09	1.02	0.43
Probiotic powder[5]	Nil	Nil	Nil	39.24	16.80
Commercial prawn feed[6]	1.30	0.62	Nil	Nil	0.64
Total[7]	1.30	6.34	14.84	53.09	23.26

[1] Total cost of individual feed used was calculated for the 17 weeks of feed trial

[2] Feeding materials: CPF = commercial prawn pellet (control); CPF+MW = commercial prawn pellet + mealworm; MW = mealworm; PMW = probiotic mealworm; CPF+PMW = Commercial prawn pellet + probiotic mealworm

[3] Mealworm cost (RM85/kg) was calculated, the total amount of mealworm used as feed in ww (kg) × purchase price (RM/kg)

[4] Wheat bran cost RM4.50/kg, an equal amount of wheat bran was used as the substrate for MW and PMW. For 1 g of mealworm in ww, 1.5 g of wheat bran was used approximately

[5] Probiotic cost (RM120/kg) was calculated, amount of probiotic powder used in PMW or CPF+PMW in ww (kg) × purchase price (RM/kg)

[6] Commercial prawn feed (RM 10/kg) was calculated as the amount of CPF used as feed in ww (kg) × purchase price (RM/kg)

[7] Total cost of feed was calculated based on total feed consumption of prawns from experimental groups

The feed/ hydration agents cost for mealworms was not included in the calculation because the products used were collected from the local market free of charge

CONCLUSION

The study demonstrated that using live mealworms as an alternative to commercial feed for GFP did not compromise prawn growth performance or survival. Notably, feeding prawns with live mealworms significantly improved their FCR and enhanced water quality, particularly by reducing nitrate concentration. The CL and CP content in the prawns did not align with that of the experimental feeds (MW, PMW, and CPF+MW), suggesting that nutrient digestibility is more influenced by fatty acid and amino acid compositions than by CL and CP content. This highlights the need to optimize fatty acid and amino acid profiles in future feed formulations to enhance nutrient absorption and utilization in prawns. However, enriching live mealworms with probiotics did not yield significant improvements in prawn growth performance, survival, or nutritional value, despite the higher costs compared to commercial feed and live mealworms alone. Therefore, the study concludes that a combination of live mealworms and commercial feed is a viable feeding strategy for GFP, while probiotic enrichment of mealworms may not offer substantial benefits to prawn productivity. Adopting live mealworms alongside commercial feeds can make prawn farming more sustainable and cost-effective, improving feed efficiency while reducing costs and supporting optimal growth.

ACKNOWLEDGMENTS

This study was financed by Universiti Tunku Abdul Rahman Research Fund (UTARRF) and awarded to the corresponding author by the Institute of Postgraduate Studies Research, UTAR, Malaysia (IPSR/RMC/UTARRF/2019-C2/T05). The authors are grateful to Pusat Penetasan Udang Galah Kg. Acheh, Malaysia for providing GFP post larvae.

REFERENCES

Ahmed, A., Lodhi, S. & Shukla, S. 2021. Observations on feeding behaviour of freshwater prawn *Macrobrachium lamarrei* (Crustacea: Decapoda). *International Journal of Fisheries and Aquatic Studies* 9(6): 109-112.

AOAC. 1997. *Official Methods of Analysis of AOAC International* Vol. 1. 16th ed. Arlington, VA, USA: Association of Official Analytical Chemists.

Barragán-Fonseca, K.Y., Greenberg, L.O., Gort, G., Dicke, M. & Van Loon, J.J. 2023. Amending soil with insect exuviae improves herbivore tolerance, pollinator attraction and seed yield of *Brassica nigra* plants. *Agriculture, Ecosystems & Environment* 342: 108219.

Barroso, F.G., de Haro, C., Sánchez-Muros, M.J., Venegas, E., Martínez-Sánchez, A. & Pérez-Bañón, C. 2014. The potential of various insect species for use as food for fish. *Aquaculture* 422: 193-201.

Berezina, N. 2017. Mealworms, promising beetles for the insect industry. In *Insects as Food and Feed: From Production to Consumption*, edited by van Huis, A. & Tomberlin, J.K. Wageningen, The Netherlands: Wageningen Academic Publishers. pp. 259-269. https://doi.org/10.3920/978-90-8686-849-0

Besson, M., Aubin, J., Komen, H., Poelman, M., Quillet, E., Vandeputte, M., van Arendonk, J.A.M. & de Boer, I.J.M. 2016. Environmental impacts of genetic improvement of growth rate and feed conversion ratio in fish farming under rearing density and nitrogen output limitations. *Journal of Cleaner Production* 116: 100-109.

Bordiean, A., Krzyżaniak, M., Aljewicz, M. & Stolarski, M.J. 2022. Influence of different diets on growth and nutritional composition of yellow mealworm. *Foods* 11(19): 3075.

Bordiean, A., Krzyżaniak, M., Stolarski, M.J., Czachorowski, S. & Peni, D. 2020. Will yellow mealworm become a source of safe proteins for Europe? *Agriculture* 10(6): 233.

Chakraborty, S.K. 2017. Ecological services of intertidal benthic fauna and the sustenance of coastal wetlands along the Midnapore (East) Coast, West Bengal, India. *Coastal Wetlands: Alteration and Remediation*, edited by Finkl, C. & Makowski, C. Springer, Cham. pp. 777-866.

Chavez, M. & Uchanski, M. 2021. Insect left-over substrate as plant fertiliser. *Journal of Insects as Food and Feed* 7(5): 683-694.

Chen, K., Li, E., Xu, Z., Li, T., Xu, C., Qin, J.G. & Chen, L. 2015. Comparative transcriptome analysis in the hepatopancreas tissue of Pacific white shrimp *Litopenaeus vannamei* fed different lipid sources at low salinity. *PLoS One* 10(12): e0144889.

Choi, I.H., Kim, J.M., Kim, N.J., Kim, J.D., Park, C., Park, J.H. & Chung, T.H. 2018. Replacing fish meal by mealworm (*Tenebrio molitor*) on the growth performance and immunologic responses of white shrimp (*Litopenaeus vannamei*). *Acta Scientiarum. Animal Sciences* 40: e35015. https://doi.org/10.4025/actascianimsci.v40i1.39077

Chong, S.H.K., Teoh, C.Y. & Wong, W.L. 2022. Potential use of live mealworm as a sustainable feed to improve productivity of the giant freshwater prawn, *Macrobrachium rosenbergii*. *ASM Science Journal* 17: 1-8. https://doi.org/10.32802/asmscj.2022.1006

Chung, M.Y., Kwon, E.Y., Hwang, J.S., Goo, T.W. & Yun, E.Y. 2013. Pre-treatment conditions on the powder of *Tenebrio molitor* for using as a novel food ingredient. *Journal of Sericultural and Entomological Science* 51(1): 9-14.

Colombo, S.M., Roy, K., Mraz, J., Wan, A.H., Davies, S.J., Tibbetts, S.M., Øverland, M., Francis, D.S., Rocker, M.M., Gasco, L. & Spencer, E. 2023. Towards achieving circularity and sustainability in feeds for farmed blue foods. *Reviews in Aquaculture* 15(3): 1115-1141.

Cruz, P.M., Ibanez, A.L., Hermosillo, O.A.M. & Ramirez Saad, H.C. 2012. Use of probiotics in aquaculture. *ISRN Microbiology* https://doi:10.5402/2012/916845

Dadvar, E., Shekarabi, S.P.H., Khazaie, E., Ehsani, J. & Mehrgan, M.S. 2023. Effect of mealworm (*Tenebrio molitor*) larvae enriched with a commercial probiotic, protexin, on growth performance and skin color in Oscar (*Astronotus ocellatus*). *Journal of Animal Environment* 14(4): 181-186.

Danks, H.V. 2006. Short life cycles in insects and mites. *The Canadian Entomologist* 138(4): 407-463.

Ding, Z., Xiong, Y., Zheng, J., Zhou, D., Kong, Y., Qi, C., Liu, Y., Ye, J. & Limbu, S.M. 2022. Modulation of growth, antioxidant status, hepatopancreas morphology, and carbohydrate metabolism mediated by alpha-lipoic acid in juvenile freshwater prawns *Macrobrachium nipponense* under two dietary carbohydrate levels. *Aquaculture* 546: 737314.

Department of Fisheries (DOF). 2023. *Annual Fisheries Statistics – Volume 1*. https://www.dof.gov.my/en/resources/fisheries-statistics-i/ Accessed 19 July 2024.

Dreassi, E., Cito, A., Zanfini, A., Materozzi, L., Botta, M. & Francardi, V. 2017. Dietary fatty acids influence the growth and fatty acid composition of the yellow mealworm *Tenebrio molitor* (Coleoptera: Tenebrionidae). *Lipids* 52(3): 285-294.

El-Dakar, A.Y. & Goher, T.M. 2004. Using of *Bacillus subtilis* in microparticulate diets for producing biosecure of *Penaeus japonicus* postlarva. *Agriculture Science Mansoura University* 29: 6855-6873.

El-Saadony, M.T., Shehata, A.M., Alagawany, M., Abdel-Moneim, A.M.E., Selim, D.A., Abdo, M., Khafaga, A.F., El-Tarabily, K.A., El-Shall, N.A. & Abd El-Hack, M.E. 2022. A review of shrimp aquaculture and factors affecting the gut microbiome. *Aquaculture International* 30(6): 2847-2869.

Finke, M.D. 2015. Complete nutrient content of three species of wild caught insects, pallid-winged grasshopper, rhinoceros beetles and white-lined sphinx moth. *Journal of Insects as Food and Feed* 1(4): 281-292.

Folch, J., Lees, M. & Sloane Stanley, G.H. 1957. A simple method for the isolation and purification of total lipids from animal tissues. *J. Boil. Chem.* 226(1): 497-509.

Gałęcki, R., Zielonka, Ł., Zasępa, M., Gołębiowska, J. & Bakuła, T. 2021. Potential utilization of edible insects as an alternative source of protein in animal diets in Poland. *Frontiers in Sustainable Food Systems* 5: 675796.

Glencross, B.D., Smith, D.M. & Williams, K.C. 1998. Effect of dietary phospholipids on digestion of neutral lipid by the prawn *Penaeus monodon*. *Journal of the World Aquaculture Society* 29(3): 365-369.

Glencross, B.D., Smith, D.M., Thomas, M.R. & Williams, K.C. 2002. The effects of dietary lipid amount and fatty-acid composition on the digestibility of lipids by the prawn, *Penaeus monodon*. *Aquaculture* 205(1-2): 157-169.

Grau, T., Vilcinskas, A. & Joop, G. 2017. Sustainable farming of the mealworm *Tenebrio molitor* for the production of food and feed. *Zeitschrift für Naturforschung C* 72(9-10): 337-349.

Gullian, M., Thompson, F. & Rodriguez, J. 2004. Selection of probiotic bacteria and study of their immunostimulatory effect in *Penaeus vannamei*. *Aquaculture* 233(1-4): 1-14.

Hai, N.V. 2015. The use of probiotics in aquaculture. *Journal of Applied microbiology* 119(4): 917-935.

Hénault-Ethier, L. 2017. The role of the emerging ento(mo)technology sector to treat urban and rural organic wastes in attaining the 2020 landfilling ban policy of Québec, Canada. *Webinar. Canadian Compost Council & Green Manitoba.*

Hoseinifar, S.H., Ashouri, G., Marisaldi, L., Candelma, M., Basili, D., Zimbelli, A., Notarstefano, V., Salvini, L., Randazzo, B., Zarantoniello, M., Pessina, A., Sojan, M.J., Vargas, A. & Carnevali, O. 2024. Reducing the use of antibiotics in European aquaculture with vaccines, functional feed additives and optimization of the gut microbiota. *Journal of Marine Science and Engineering* 12(2): 204. https://doi.org/10.3390/jmse12020204

Hua, K., Cobcroft, J.M., Cole, A., Condon, K., Jerry, D.R., Mangott, A., Praeger, C., Vucko, M.J., Zeng, C., Zenger, K. & Strugnell, J.M. 2019. The future of aquatic protein: Implications for protein sources in aquaculture diets. *One Earth* 1(3): 316-329.

Irungu, F.G., Mutungi, C.M., Faraj, A.K., Affognon, H., Tanga, C., Ekesi, S., Nakimbugwe, D. & Fiaboe, K.K.M. 2018. Minerals content of extruded fish feeds containing cricket (*Acheta domesticus*) and black soldier fly larvae (*Hermetia illucens*) fractions. *International Aquatic Research* 10: 101-113.

Jeong, S.M., Khosravi, S., Kim, K.W., Lee, B.J., Hur, S.W., You, S.G. & Lee, S.M. 2022. Potential of mealworm, *Tenebrio molitor*, meal as a sustainable dietary protein source for juvenile black porgy, *Acanthopagrus schlegelii*. *Aquaculture Reports* 22: 100956.

Karthik, M., Bhavan, P.S. & Manjula, T. 2018. Growth promoting potential and colonization ability of probiotics (*Bacillus coagulans* and *Bacillus subtilis*) on the freshwater prawn *Macrobrachium rosenbergii* post-larvae. *Insights in Biology and Medicine* 2*:* 7-18.

Kewcharoen, W. & Srisapoome, P. 2019. Probiotic effects of *Bacillus* spp. from Pacific white shrimp (*Litopenaeus vannamei*) on water quality and shrimp growth, immune responses, and resistance to *Vibrio parahaemolyticus* (AHPND strains). *Fish & Shellfish Immunology* 94: 175-189.

Khalid, H.N.M., Jafri, N.A., Kari, Z.A., Mat, K., Rusli, N.D., Mahmud, M., Al-Amsyar, S.M., Sukri, S.A.M. & Harun, H.C. 2023. Effects of different inclusion rates of pre-treated rubber seed meal (RSM) on physicochemical properties of juvenile *Macrobrachium rosenbergii* feed. *IOP Conference Series: Earth and Environmental Science* 1286: 012036. https://doi.org/10.1088/1755-1315/1286/1/012036

Khanjani, M.H., Torfi Mozanzade, M., Sharifinia, M. & Emerenciano, M.G.C. 2023. Biofloc: A sustainable dietary supplement, nutritional value and functional properties. *Aquaculture* 562: 738-757.

Khosravi, S., Kim, E., Lee, Y.S. & Lee, S.M. 2018. Dietary inclusion of mealworm (*Tenebrio molitor*) meal as an alternative protein source in practical diets for juvenile rockfish (*Sebastes schlegeli*). *Entomological Research* 48(3): 214-221.

Kim, S.Y., Park, J.B., Lee, Y.B., Yoon, H.J., Lee, K.Y. & Kim, N.J. 2015. Growth characteristics of mealworm *Tenebrio molitor*. *Journal of Sericultural and Entomological Science* 53(1): 1-5.

Kolanchinathan, P., Kumari, P.R., Gnanam, T.S., John, G. & Balasundaram, A. 2017. Performance evaluation of two probiotic species, on the growth, body composition and immune expression in *Penaeus monodon*. *Journal of Fisheries and Aquatic Science* 12: 157-167.

Kolanchinathan, P., Kumari, P.R., Raja, K., John, G. & Balasundaram, A. 2022. Analysis of feed composition and growth parameters of *Penaeus monodon* supplemented with two probiotic species and formulated diet. *Aquaculture* 549: 737740. https://doi.org/10.1016/j.aquaculture.2021.737740

Kulkarni, A., Krishnan, S., Anand, D., Kokkattunivarthil Uthaman, S., Otta, S.K., Karunasagar, I. & Kooloth Valappil, R. 2021. Immune responses and immunoprotection in crustaceans with special reference to shrimp. *Reviews in Aquaculture* 13(1): 431-459.

Kumar, V., Sinha, A.K., Romano, N., Allen, K.M., Bowman, B.A., Thompson, K.R. & Tidwell, J.H. 2018. Metabolism and nutritive role of cholesterol in the growth, gonadal development, and reproduction of crustaceans. *Reviews in Fisheries Science & Aquaculture* 26(2): 254-273.

Lin, W., Luo, H., Wu, J., Hung, T.C., Cao, B., Liu, X., Yang, J. & Yang, P. 2022. A review of the emerging risks of acute ammonia nitrogen toxicity to aquatic decapod crustaceans. *Water* 15(1): 27. https://doi.org/10.3390/w15010027

López-Almonte, O.H., Hernández-Simón, L.M. & Aguilar-Guggembuhl, J. 2024. Costa Rica's potential for entotechnology development: An ecosystem and entomophagy perspective. *Journal of Insects as Food and Feed* 11(2): 317-327. https://doi.org/10.1163/23524588-00001238

Mancini, S., Fratini, F., Turchi, B., Mattioli, S., Dal Bosco, A., Tuccinardi, T., Nozic, S. & Paci, G. 2019. Former foodstuff products in *Tenebrio molitor* rearing: Effects on growth, chemical composition, microbiological load, and antioxidant status. *Animals* 9(8): 484.

Mohideen, A.K. 2022. *Crack the Whip on Food Waste*. Consumers' Association of Penang Press Statement. https://consumer.org.my/crack-the-whip-on-foodwaste/#:~:text=Malaysians%20dumped%204%2C046%20tonnes%20of,waste%20per%20day%20in%202021 (Accessed 10 October 2023).

Motte, C., Rios, A., Lefebvre, T., Do, H., Henry, M. & Jintasataporn, O. 2019. Replacing fish meal with defatted insect meal (yellow mealworm *Tenebrio molitor*) improves the growth and immunity of pacific Pacific white shrimp (*Litopenaeus vannamei*). *Animals* 9(5): 258.

Murawska, D., Daszkiewicz, T., Sobotka, W., Gesek, M., Witkowska, D., Matusevičius, P. & Bakuła, T. 2021. Partial and total replacement of soybean meal with full-fat black soldier fly (*Hermetia illucens* L.) larvae meal in broiler chicken diets: Impact on growth performance, carcass quality and meat quality. *Animals* 11(9): 2715. https://doi.org/10.3390/ani11092715

Nathanailides, C., Kolygas, M., Choremi, K., Mavraganis, T., Gouva, E., Vidalis, K. & Athanassopoulou, F. 2021. Probiotics have the potential to significantly mitigate the environmental impact of freshwater fish farms. *Fishes* 6(4): 76. https://doi.org/10.3390/fishes6040076

Ng, W.K., Lim, C.L., Romano, N. & Kua, B.C. 2017. Dietary short-chain organic acids enhanced resistance to bacterial infection and hepatopancreatic structural integrity of the giant freshwater prawn, *Macrobrachium rosenbergii*. *International Aquatic Research* 9: 293-302.

Nimrat, S., Suksawat, S., Boonthai, T. & Vuthiphandchai, V. 2012. Potential *Bacillus* probiotics enhance bacterial numbers, water quality and growth during early development of white shrimp (*Litopenaeus vannamei*). *Veterinary Microbiology* 159(3-4): 443-450.

Nunes, A.J., Sá, M.V., Browdy, C.L. & Vazquez-Anon, M. 2014. Practical supplementation of shrimp and fish feeds with crystalline amino acids. *Aquaculture* 431: 20-27.

Oonincx, D.G., Laurent, S., Veenenbos, M.E. & van Loon, J.J. 2020. Dietary enrichment of edible insects with omega 3 fatty acids. *Insect Science* 27(3): 500-509.

Oonincx, D.G., van Broekhoven, S., van Huis, A. & van Loon, J.J. 2015. Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. *PLoS ONE* 10(12): e0144601.

Panini, R.L., Freitas, L.E.L., Guimarães, A.M., Rios, C., da Silva, M.F.O., Vieira, F.N., Fracalossi, D.M., Samuels, R.I., Prudêncio, E.S., Silva, C.P. & Amboni, R.D. 2017. Potential use of mealworms as an alternative protein source for Pacific white shrimp: Digestibility and performance. *Aquaculture* 473: 115-120.

Paris, N., Fortin, A., Hotte, N., Zadeh, A.R., Jain, S. & Hénault-Ethier, L. 2024. Developing an environmental assessment framework for an insect farm operating in circular economy: The case study of a Montréal (Canada) mealworm farm. *Journal of Cleaner Production* 460: 142450. https://doi.org/10.1016/j.jclepro.2024.142450

Parolini, M., Ganzaroli, A. & Bacenetti, J. 2020. Earthworm as an alternative protein source in poultry and fish farming: Current applications and future perspectives. *Science of the Total Environment* 734: 139460.

Patel, S. 2019. Insects as a source of sustainable proteins. *Proteins: Sustainable Source, Processing and Applications* 1(2): 41-61.

Paul, P. & Rahman, M.A. 2016. Growth performance of fresh water prawn *Macrobrachium rosenbergii* under different supplemental feeding options. *International Journal of Fisheries and Aquatic Studies* 4(2): 203-207.

Pillai, B.R., Ponzoni, R.W., Das Mahapatra, K. & Panda, D. 2022. Genetic improvement of giant freshwater prawn *Macrobrachium rosenbergii*: A review of global status. *Reviews in Aquaculture* 14(3): 1285-1299.

Ramos-Elorduy, J., González, E.A., Hernández, A.R. & Pino, J.M. 2002. Use of *Tenebrio molitor* (Coleoptera: Tenebrionidae) to recycle organic wastes and as feed for broiler chickens. *Journal of Economic Entomology* 95(1): 214-220.

Rana, K.J., Siriwardena, S. & Hasan, M.R. 2009. *Impact of Rising Feed Ingredient Prices on Aquafeeds and Aquaculture Production* [pdf] Sterling: Food and Agriculture Organization of the United Nations (FAO). https://www.cabdirect.org/cabdirect/abstract/20103269836 (Accessed 2 April 2023).

Romano, N. & Zeng, C. 2013. Toxic effects of ammonia, nitrite, and nitrate to decapod crustaceans: A review on factors influencing their toxicity, physiological consequences, and coping mechanisms. *Reviews in Fisheries Science* 21(1): 1-21. https://doi.org/10.1080/10641262.2012.753404

Rumbos, C.I., Karapanagiotidis, I.T., Mente, E., Psofakis, P. & Athanassiou, C.G. 2020. Evaluation of various commodities for the development of the yellow mealworm, *Tenebrio molitor*. *Scientific Reports* 10(1): 11224.

Rumpold, B.A. & Schlüter, O.K. 2013. Potential and challenges of insects as an innovative source for food and feed production. *Innovative Food Science & Emerging Technologies* 17: 1-11.

Sabaté, J. & Soret, S. 2014. Sustainability of plant-based diets: Back to the future. *The American Journal of Clinical Nutrition* 100(suppl_1): 476S-482S. https://doi.org/10.3945/ajcn.113.071522

Sales, J. & Glencross, B. 2011. A meta-analysis of the effects of dietary marine oil replacement with vegetable oils on growth, feed conversion and muscle fatty acid composition of fish species. *Aquaculture Nutrition* 17(2): e271-e287.

Sarman, V., Vishal, R., Mahavadiya, D. & Sapra, D. 2018. Nutritional aspect for freshwater prawn (*Macrobrachium rosenbergii*) farming. *International Journal of Fauna and Biological Studies* 5(2): 172-175.

Seenivasan, C., Radhakrishnan, S., Muralisankar, T. & Bhavan, P.S. 2012. *Bacillus subtilis* on survival, growth, biochemical constituents and energy utilization of the freshwater prawn *Macrobrachium rosenbergii* post larvae. *The Egyptian Journal of Aquatic Research* 38(3): 195-203.

Seidel, R.A., Schaefer, R.L. & Donaldson, T.J. 2007. The role of cheliped autotomy in the territorial behavior of the freshwater prawn *Macrobrachium* lar. *Journal of Crustacean Biology* 27(2): 197-201.

Sharifinia, M., Bahmanbeigloo, Z.A., Keshavarzifard, M., Khanjani, M.H., Daliri, M., Koochaknejad, E. & Jasour, M.S. 2023a. The effects of replacing fishmeal by mealworm (*Tenebrio molitor*) on digestive enzymes activity and hepatopancreatic biochemical indices of *Litopenaeus vannamei*. *Annals of Animal Science* https://doi.org/10.2478/aoas-2022-0098

Sharifinia, M., Bahmanbeigloo, Z.A., Keshavarzifard, M., Khanjani, M.H., Daliri, M., Koochaknejad, E. & Jasour, M.S. 2023b. Fishmeal replacement by mealworm (*Tenebrio molitor)* in diet of farmed Pacific white shrimp (*Litopenaeus vannamei*): Effects on growth performance, serum biochemistry, and immune response. *Aquatic Living Resources* https://doi.org/10.1051/alr/2023013

Siemianowska, E., Kosewska, A., Aljewicz, M., Skibniewska, K., Polak-Juszczak, L., Jarocki, A. & Jędras, M. 2013. Larvae of mealworm (*Tenebrio molitor* L.) as European novel food. *Agricultural Sciences* 4(6): 287-291.

Teoh, C.Y. & Loo, E.V. 2022. Potential of Safmannan as a feed additive for juvenile African catfish (*Clarias gariepinus*): Growth, feed utilization efficiency, serum lysozyme activity, and total viable bacterial count in the gut. *Journal of Applied Aquaculture* 35(4): 865-877. https://doi.org/10.1080/10454438.2022.2034702

Teoh, C.Y. & Ng, W.K. 2016. The implications of substituting dietary fish oil with vegetable oils on the growth performance, fillet fatty acid profile and modulation of the fatty acid elongase, desaturase and oxidation activities of red hybrid tilapia, *Oreochromis* sp. *Aquaculture* 465: 311-322.

Turchini, G.M., Torstensen, B.E. & Ng, W.K. 2009. Fish oil replacement in finfish nutrition. *Reviews in Aquaculture* 1(1): 10-57. https://doi:10.1111/j.1753-5131.2008.01000.x

Tocher, D.R. & Glencross, B.D. 2015. Lipids and fatty acids. In *Dietary Nutrients, Additives, and Fish Health*, edited by Lee, C.S., Lim, C., Gatlin III, D.M. & Webster, C.D. Hoboken, NJ: John Wiley & Sons. pp. 47-94.

Toledo, A., Frizzo, L., Signorini, M., Bossier, P. & Arenal, A. 2019. Impact of probiotics on growth performance and shrimp survival: A meta-analysis. *Aquaculture* 500: 196-205.

van Huis, A. 2013. Potential of insects as food and feed in assuring food security. *Annual Review of Entomology* 58: 563-583.

van Huis, A. & Oonincx, D.G. 2017. The environmental sustainability of insects as food and feed. A review. *Agronomy for Sustainable Development* 37: 43.

Xie, S., Liu, Y., Tian, L., Niu, J. & Tan, B. 2020. Low dietary fish meal induced endoplasmic reticulum stress and impaired phospholipids metabolism in juvenile pacific white shrimp, *Litopenaeus vannamei*. *Frontiers in Physiology* 11: 1024. https://doi: 10.3389/fphys.2020.01024

Zokaeifar, H., Luis Balcázar, J., Kamarudin, M.S., Sijam, K., Arshad, A. & Saad, C.R. 2012. Selection and identification of non-pathogenic bacteria isolated from fermented pickles with antagonistic properties against two shrimp pathogens. *The Journal of Antibiotics* 65(6): 289-294.

*Corresponding author; email: cyteoh@utar.edu.my