Int. J. Aquat. Biol. (2026) 14(4): 101-112
ISSN: 2322-5270; P-ISSN: 2383-0956
Journal homepage: www.ij-aquaticbiology.com

Original Article

Evaluating insect-based feeds as sustainable alternatives to trash fish for spiny lobster (*Panulirus* sp.): Implications for growth efficiency and feeding behavior

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Abstract: The rapid increase in global demand for spiny lobster (*Panulirus* sp.) has intensified pressure on wild stocks and highlighted the urgent need for sustainable aquaculture development. In Indonesia, lobster farming remains heavily dependent on trash fish as the primary feed source, despite associated challenges related to sustainability, biosecurity, and environmental degradation. This study evaluated the potential of insect-based feeds—Black soldier fly (*Hermetia illucens*) maggots and mealworms (*Tenebrio molitor*)—as sustainable alternatives to trash fish by examining their effects on growth performance and feeding behavior of spiny lobster under controlled conditions. A 30-day experiment was conducted using a Completely Randomized Design with three feed treatments (trash fish, BSF maggots, and mealworms), each replicated three times. Lobsters were fed daily at 5% of body weight, and growth parameters, feeding response, feed utilization, and water quality were monitored. The results showed that lobsters fed trash fish achieved significantly higher absolute weight gain (6.47 g) and length increment (0.39 cm) compared with those fed mealworms (1.67 g; 0.09 cm) and BSF maggots (0.93 g; 0.13 cm). Feeding behavior analysis revealed faster approach times and longer consumption durations in the trash fish treatment, indicating higher palatability and stronger chemosensory stimulation. Water quality remained within optimal ranges across all treatments, confirming that growth differences were primarily feed-driven. Although insect-based feeds demonstrated nutritional potential and supported positive growth and survival, their performance was inferior to that of trash fish. These findings suggest that successful replacement of trash fish requires improved formulation strategies, including attractant supplementation, enhanced digestibility, and adaptation periods, to optimize the effectiveness of insect-based feeds for sustainable lobster aquaculture.

Article history:
Received 20 February 2026
Accepted 27 May 2026
Available online 25 August 2026

Keywords:
Spiny lobster
Black soldier fly
Mealworm
Trash fish

Introduction

Spiny lobster (*Panulirus* sp.) represents one of the most economically valuable fisheries commodities in Indonesia and many tropical regions, with demand that continues to rise in both national and international markets. Globally, spiny lobster is widely regarded as a luxury seafood product, particularly in East Asian markets, where rising incomes and shifting dietary preferences have driven a substantial surge in demand. Recent estimates indicate that global lobster demand has increased by approximately 15%, intensifying pressure on natural stocks and amplifying the economic importance of this commodity for coastal communities and exporting countries (Yeap et al., 2022; Sahidhir et al., 2023; Ooi et al., 2023). This trend is clearly reflected in Indonesia, where live lobster exports reached 682,870 individuals in January 2021 alone, averaging 42,679 lobsters per day, underscoring the strong market pull and the strategic value of lobster fisheries to the national economy.

Despite this growing demand, the supply of spiny lobster from capture fisheries remains inherently limited. The estimated potential yield of Indonesian lobster fisheries is approximately 4,900 tons per year, which is insufficient to meet current and projected market requirements. Overreliance on wild capture has therefore raised serious concerns regarding stock depletion, ecological sustainability, and long-term economic viability. As wild populations decline or become increasingly regulated, the development of

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DOI: https://doi.org/10.22034/ijab.v14i4.2822

spiny lobster aquaculture has emerged as an urgent priority to ensure a stable and sustainable supply while reducing pressure on natural ecosystems (Yeap et al., 2022; Sudewi et al., 2024). Across different regions, including Europe and the Asia-Pacific, aquaculture research on species such as *Palinurus elephas* and *P. homarus* has expanded rapidly, reflecting a global consensus that farming systems must play a central role in meeting future demand (Nankervis and Jones, 2022; Sudewi et al., 2024).

Although spiny lobster aquaculture offers substantial promise, its development is constrained by several technical and economic challenges, among which feed management is consistently identified as the most critical bottleneck. Feed costs typically account for the largest proportion of operational expenditure in lobster farming, contributing approximately 50-60% of total production costs, or at least 40-50% depending on the production system and feed source used (Nankervis and Jones, 2022; Ooi et al., 2023). In Indonesia and many other lobster-producing regions, grow-out operations still rely heavily on trash fish, which may constitute up to 70% of total feed inputs. Trash fish is favored primarily because of its immediate availability, perceived palatability, and relatively low upfront cost, particularly in areas with abundant fisheries bycatch (Sudewi et al., 2024).

However, the continued dependence on trash fish presents substantial sustainability, biosecurity, and environmental challenges. From a sustainability perspective, trash fish consists largely of small pelagic fish and mixed bycatch species, many of which are already under fishing pressure. The large-scale diversion of these resources for aquaculture feed exacerbates overexploitation of non-target species, reduces biodiversity, and disrupts local marine food webs (Nankervis and Jones, 2022). Nutritionally, trash fish is also highly variable in composition, resulting in inconsistent growth performance and health outcomes in cultured lobsters (Sudewi et al., 2021). Inefficient nutrient utilization further increases feed wastage, undermining production efficiency.

Biosecurity risks are an additional concern associated with the use of trash fish. Raw or minimally processed trash fish is highly susceptible to microbial contamination and may act as a vector for pathogens, increasing the risk of disease outbreaks in intensive aquaculture systems (Ooi et al., 2023). Disease transmission not only compromises lobster survival and growth but also threatens surrounding ecosystems if pathogens spread beyond farm boundaries. Environmentally, the high organic load from uneaten trash fish and fecal waste can rapidly degrade water quality, promoting eutrophication, oxygen depletion, and harmful algal blooms, all of which negatively affect cultured organisms and surrounding habitats (Sudewi et al., 2021; Nankervis and Jones, 2022). Collectively, these issues have prompted increasing scrutiny of trash fish–based feeding strategies and intensified calls for sustainable alternatives.

In response, formulated feeds based on alternative protein sources are increasingly being explored to enhance production efficiency, improve biosecurity, and reduce environmental impacts. Among these alternatives, insect-based feeds have gained particular attention within the framework of sustainable aquaculture and the circular bioeconomy. Insects such as the black soldier fly (*Hermetia illucens*) and the mealworm (*Tenebrio molitor*) can efficiently convert organic waste streams into high-quality biomass, thereby closing nutrient loops and reducing waste generation in agro-food systems (Saputra et al., 2024). This production model aligns strongly with circular bioeconomy principles, transforming low-value organic residues into valuable feed resources while minimizing reliance on finite marine inputs.

From a nutritional standpoint, insect meals exhibit characteristics that are highly relevant to crustacean nutrition. Black soldier fly larvae typically contain approximately 40-60% crude protein on a dry matter basis, along with a balanced profile of essential amino acids required for growth and tissue synthesis in crustaceans (Saputra and Fotedar, 2024). Similarly, mealworms are reported to contain 47.2-60.3% crude protein and high lipid levels ranging from 31.1-43.1%, with favorable amino acid profiles, including lysine, which is often limiting in conventional fish-based feeds (Iwai et al., 2021; Supriyono et al., 2022; Genodepa et al., 2023). These attributes position insect-based feeds as promising candidates to partially or fully replace trash fish and fishmeal in lobster aquaculture diets.

Nevertheless, despite their nutritional potential and sustainability advantages, the direct substitution of trash fish with insect-based feeds in marine spiny lobster culture remains insufficiently understood. Existing studies have primarily focused on formulated feeds or partial inclusion of insect meals, often emphasizing growth performance or survival in isolation. Comparative studies that directly evaluate trash fish, black soldier fly maggots, and mealworms as whole feeds under controlled conditions are still limited, particularly for *Panulirus* sp. Moreover, spiny lobsters exhibit complex feeding behaviors driven by chemosensory cues, palatability, and feed texture, meaning that nutritional adequacy alone does not guarantee effective feed utilization. Feeding behavior, including approach response and consumption dynamics, plays a decisive role in determining growth efficiency and overall production outcomes.

Several key research gaps therefore persist. First, there is a lack of comprehensive performance metrics comparing insect-based feeds with traditional trash fish diets over defined grow-out periods, particularly in terms of absolute weight gain, length increment, and feed utilization efficiency (Sahidhir et al., 2023; Codabaccus et al., 2025). Second, the acceptability and digestibility of insect-based feeds across different lobster life stages remain poorly characterized, particularly regarding essential amino acids, fatty acids, and micronutrient availability (Lubis et al., 2023; Amin et al., 2024). Third, limited information is available on how insect-based feeds influence lobster behavior, stress responses, and potential cannibalistic interactions, all of which are critical determinants of survival and growth in intensive systems (Codabaccus et al., 2025; Faturrahman et al., 2025). Finally, broader evaluations that address environmental impact and economic feasibility, including life cycle assessments and cost–benefit analyses, remain scarce (Kotiya and Vadher, 2021).

Given these knowledge gaps, evaluating insect-based feeds as sustainable alternatives to trash fish under controlled rearing conditions is both timely and necessary. Controlled systems enable precise observation of feeding behavior, growth response, and feed efficiency, while minimizing confounding environmental variability. The present study, therefore, aims to provide direct comparative evidence on the effects of different feed types—trash fish, black soldier fly maggots, and mealworms—on the growth performance and feeding behavior of spiny lobster (*Panulirus* sp.). It is hypothesized that feed type significantly influences lobster growth, with trash fish expected to yield superior performance due to higher palatability and dietary familiarity, while insect-based feeds may offer sustainability benefits but lower growth efficiency in their unmodified form. By integrating growth metrics with behavioral observations, this study seeks to advance understanding of the mechanisms underlying feed performance in lobster aquaculture. The findings are expected to support evidence-based decision-making in developing sustainable lobster feeds and contribute to the broader transition away from environmentally and biosecurity-compromising trash fish toward more resilient and circular feeding strategies.

Materials and Methods

The experiment was conducted over a 30-day period from March to April 2025. The study took place in Kuranji Village, Kuranji Dalang Hamlet, Labu Api District, West Lombok Regency, West Nusa Tenggara Province, Indonesia. This location represents a small-scale, controlled aquaculture setting that reflects typical lobster grow-out conditions in coastal Indonesia while allowing close monitoring of feeding behavior, growth performance, and water quality under experimental conditions.

The study employed a Completely Randomized Design (CRD) to evaluate the effects of different feed types on the growth performance and feeding behavior of spiny lobster (*Panulirus* sp.). CRD is widely applied in lobster nutrition trials to minimize experimental bias and isolate treatment effects under

Table 1. Crude protein content of experimental feeds (dry matter basis).

Feed type	Crude protein (%)
Trash fish	65±0.7
BSF maggots	42±1.1
Mealworms	47.2±1.3

Note: The values represent the crude protein content of experimental feeds, measured in three replicates. The standard deviations (±) indicate the variability of each feed type.

controlled conditions (Sudewi et al., 2021; Sahidhir et al., 2023). Three feeding treatments were tested, each with three independent replications, resulting in a total of nine experimental units. The feeding treatments consisted of trash fish (P1), Black Soldier Fly (*Hermetia illucens*) maggots (P2), and mealworms (*Tenebrio molitor*) (P3). A daily feeding rate of 5% of lobster body weight was applied across all treatments, consistent with recommended feeding rates for juvenile *Panulirus* spp. reported in controlled growth trials (Kropielnicka-Kruk et al., 2022). Treatment allocation to experimental units was randomized using a lot-drawing method to minimize bias and ensure that observed differences were attributable to feed type rather than environmental variation.

All equipment used in this study was selected to ensure accurate measurement of the parameters studied. Rearing was conducted in fiber tanks, with water quality meticulously monitored using a pH meter, a DO (dissolved oxygen) meter, a thermometer, and a refractometer for salinity. An aerator maintained adequate oxygen levels. Organism growth was quantified by measuring body weight with an analytical balance and length with a ruler. PVC pipes and baskets were utilized as shelters and for the physical separation of experimental units, respectively. A camera provided visual documentation, while all observational data were systematically recorded using standard stationery.

To ensure the study's validity, all materials, including the experimental organisms, rearing medium, and nutritional inputs, were carefully selected and standardized. Post-larval marine lobsters (*Panulirus homarus* or similar, as relevant) served as the test organism. They were reared in a controlled environment using filtered and aerated natural seawater as the medium. The primary experimental variable consisted of three distinct feed treatments: Black Soldier Fly (*Hermetia illucens*) maggots, chopped trash fish, and mealworms (*Tenebrio molitor* larvae), each evaluated for their effect on growth performance and survival.

Nutritional composition of experimental feeds: The crude protein (CP) content of the experimental feeds was analyzed using the Kjeldahl method. All protein values were expressed on a dry matter basis to ensure comparability among feed types. The feed ingredients evaluated in this study included trash fish, black soldier fly (BSF) maggots, and mealworms. The mean crude protein values and their corresponding standard deviations are presented in Table 1.

Experimental procedures

Preparation of rearing containers: Rectangular fiber tanks with a maximum capacity of 500 L were used. Each tank was filled with seawater to a depth of approximately 50 cm. Plastic baskets measuring 80×60 cm were placed inside the tanks to separate experimental units and prevent direct interaction between lobsters from different treatments. Each basket was equipped with PVC pipes that functioned as shelters to reduce stress and aggressive interactions. Prior to stocking, all tanks and baskets were thoroughly cleaned using detergent, rinsed with freshwater, and air-dried. Continuous aeration was provided throughout the experimental period to maintain adequate dissolved oxygen levels.

Preparation and acclimatization: Spiny lobsters (*Panulirus* sp.) used in the experiment were obtained from local fishermen in Teluk Ekas, East Lombok. Upon arrival at the experimental site, lobsters were acclimatized to the rearing environment for approximately 1-2 hours to reduce handling stress. During acclimatization, water temperature and salinity were gradually adjusted to match the experimental conditions. Each lobster was weighed individually on an analytical balance to determine its initial body weight prior to stocking in the experimental baskets.

Rearing and maintenance: Lobsters were reared for 30 consecutive days. Five individuals were stocked in each experimental basket, resulting in uniform stocking density across treatments. Feeding was conducted daily according to the assigned treatment at a ration equivalent to 5% of total body weight (Radford and Marsden, 2005; Cox and Davis, 2006). Uneaten feed and fecal waste were removed daily through siphoning to maintain water quality. Partial water exchange of approximately 10% of the total volume was conducted once per week. Water quality parameters, including temperature, pH, salinity, and dissolved oxygen, were measured weekly using appropriate instruments.

Studied parameters and data analysis

***Absolute weight growth*:** Absolute weight growth was calculated as the difference between final body weight (Wt) and initial body weight (Wo) at the end of the rearing period, expressed in grams, using the formula of W = Wt – Wo (Lamek et al., 2011; Marlina and Nursandi, 2021; Slamet et al., 2021; Giri and Slamet, 2023).

***Absolute length growth*:** Absolute length growth was determined as the difference between final body length (Lt) and initial body length (Lo), expressed in centimeters, using the formula of L = Lt – Lo (Amali and sari, 2020; Giri and Slamet, 2023).

***Feed approach time*:** In lobster feeding behavior studies, feed approach time is defined as the time it takes lobsters to move toward and engage with food after it is detected. This measure is crucial for understanding foraging efficiency and habitat preferences across lobster species, as it provides insights into their metabolic requirements and behavioral ecology under varying feed availability and types (Kropielnicka-Kruk et al., 2022; Rivaie et al., 2023; Peters et al., 2024). This can involve video cameras or direct visual observation in controlled experiments (Peters et al., 2024; Lubis et al., 2024).

Feed consumption time: Feed consumption time (FCT) was quantified as feeding latency, measured directly via visual observation by the same observer using a stopwatch. At each scheduled feeding event, the stopwatch was started immediately when the feed was introduced into the rearing unit and stopped when the lobster first approached the feed (i.e., directed movement toward the feed source indicating feeding intent). Observations were continued for up to 60 min after feed introduction; a positive feeding response was recorded when lobsters approached the feed in < 1 h, while individuals that did not approach within this period were recorded as no-response (latency censored at 3600 s). This operational definition and latency-based assessment were adapted from Peters et al. (2024).

Water quality parameters: During the experiment, key parameters—temperature, pH, salinity, and dissolved oxygen (DO)—were monitored to maintain stable rearing conditions for lobster growth. Measurements were taken weekly using calibrated instruments/sensors, complemented by routine visual inspections of the culture units. Standard husbandry practices (e.g., removal of organic debris and biofouling) were applied to maintain reading accuracy and environmental stability. Weekly results were used to guide corrective actions (e.g., water exchange and/or aeration) to minimize fluctuations, particularly in pH and salinity, which are critical for crustacean health and performance (Berthod et al., 2021). DO was closely monitored due to its role in aerobic metabolism and maintained at levels generally considered adequate for culture performance (typically>5 mg/L) to reduce physiological stress (Berthod et al., 2021). Integrated monitoring of these physicochemical variables supports interpretation of environmental effects on lobster responses and culture outcomes (Chaurasiya et al., 2023).

Statistical analysis: Growth and feeding behavior data were analyzed using Analysis of Variance (ANOVA) at a significance level of 5% ($\alpha = 0.05$), a commonly used approach in crustacean nutrition and feeding studies to compare treatment means (Sudewi et al., 2024). When significant differences among treatments were detected, Duncan's Multiple Range Test was applied to identify pairwise differences between treatment means. Water quality data were analyzed descriptively without inferential statistical

Table 2. Initial and final body weight of lobsters during the experiment.

Treatment	Average initial weight (g) Mean±SD	Average final weight (g) Mean±SD
Trash fish (P1)	111.3±3.1	117.8±3.65
BSF maggots (P2)	112.3±1.45	113.2±1.56
Mealworms (P3)	111.8±1.22	113.5±1.22

Table 3. Initial and final body length of lobsters during the experiment

Treatment	Average initial length (cm) Mean±SD	Average final length (cm) Mean±SD
Trash fish (P1)	5.99±0.034	6.38±0.016
BSF maggots (P2)	5.98±0.032	6.11±0.120
Mealworms (P3)	5.98±0.071	6.07±0.089

testing, following standard practice in short-term controlled aquaculture trials where environmental parameters are maintained within optimal ranges (Espinosa-Magaña et al., 2022).

Results

Average initial and final body weight of lobsters during the experiment: Table 2 shows the average initial and final body weight of lobsters fed three different diets: trash fish (P1), BSF maggots (P2), and mealworms (P3). Lobsters in the trash fish group (P1) showed the highest growth, with a weight increase of 6.5 g (from 111.3 g to 117.8 g). In contrast, the BSF maggot group (P2) had minimal growth, increasing only by 0.9 g (from 112.3 g to 113.2 g). The mealworm group (P3) exhibited a moderate growth of 1.7 g (from 111.8 g to 113.5 g) (Table 2). These findings suggest that trash fish is the most effective feed, while BSF maggots show limited growth potential in lobsters.

Absolute weight growth of spiny lobster: After 30 days of rearing, spiny lobsters in all treatments exhibited an increase in body weight, although the magnitude of growth varied markedly among feed types. The results showed that the feed type had a significant effect on absolute weight growth. Lobsters fed trash fish (P1) showed the highest growth performance, followed by those fed mealworms (P3), while lobsters fed Black Soldier Fly (BSF) maggots (P2) exhibited the lowest weight gain (Fig. 1). The mean absolute weight gains were 6.47 g for P1, 0.93 g for P2, and 1.67 g for P3. Lobsters fed trash fish differed significantly from those fed BSF maggots and mealworms, whereas no significant difference was detected between the BSF and mealworm treatments.

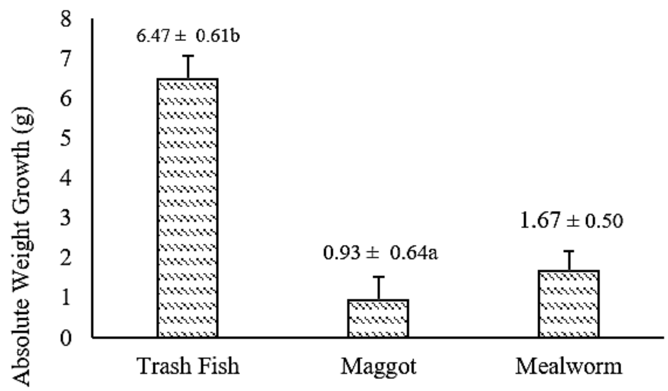

Figure 1. Absolute weight growth of spiny lobster (*Panulirus* sp.) under different feeding treatments.

Average initial and final body length of lobsters: Lobsters fed trash fish (P1) exhibited the highest growth, with an increase in body length from 5.99 cm to 6.38 cm. In contrast, the lowest growth was observed in lobsters fed mealworms (P3), with body length increasing from 5.98 cm to 6.07 cm, highlighting the varying effectiveness of different feed types (Table 3).

Absolute length growth of spiny lobster: Lobster body length increased across all treatments during the 30-day experimental period. The results revealed a significant effect of feed type on absolute length growth (P<0.05). Consistent with weight growth results, the trash fish treatment produced the greatest increase in length, followed by BSF maggots and mealworms. Mean absolute length growth values were 0.39 cm for P1, 0.13 cm for P2, and 0.09 cm for P3.

Table 4. Water quality parameters recorded during the experiment.

Treatment	Temperature (°C)	pH	Salinity (ppt)	Dissolved oxygen (mg L^{-1})
Trash Fish	27–29	7.6	30-35	7.9-8.5
Maggot	27–29	7.6	30-35	7.1-8.5
Mealworm	27–29	7.6	30-35	7.1-8.5
Optimal range	23–32	4.0–8.5	30-35	4.6-9.6

The trash fish treatment differed significantly from both insect-based feed treatments, while no significant difference was observed between BSF maggots and mealworms (Fig. 2).

Feed approach time (feed attraction test): Feed approach time differed significantly among feeding treatments. Lobsters exhibited the fastest response to trash fish, indicating higher feed attractiveness and palatability. Slower approach times were observed in lobsters fed BSF maggots and mealworms, suggesting lower initial attraction compared to fish-based feed. These results demonstrate that feed type strongly influences feeding response behavior in spiny lobsters (Fig. 3).

Feed consumption time: It varied significantly among treatments. Lobsters fed trash fish required the longest time to consume the feed, indicating prolonged handling and ingestion activity. In contrast, lobsters fed BSF maggots and mealworms consumed their feed more rapidly. The results confirmed a significant effect of feed type on consumption duration (P<0.05). Mean feed consumption times were 416.7 seconds for trash fish (P1), 74.0 seconds for BSF maggots (P2), and 56.0 seconds for mealworms (P3) (Fig. 4).

Specific growth rate: SGR varied among treatments, reflecting differences in relative growth efficiency associated with feed type. Lobsters fed trash fish exhibited the highest SGR, followed by mealworms and BSF maggots. Although insect-based feeds supported positive growth, their SGR values were lower than those obtained with trash fish, indicating reduced efficiency in promoting relative biomass increase over the experimental period (Fig. 5).

Survival rate: Survival rates remained high across all treatments throughout the 30-day rearing period, with no mass mortality observed. Minor differences in survival were observed among treatments; however,

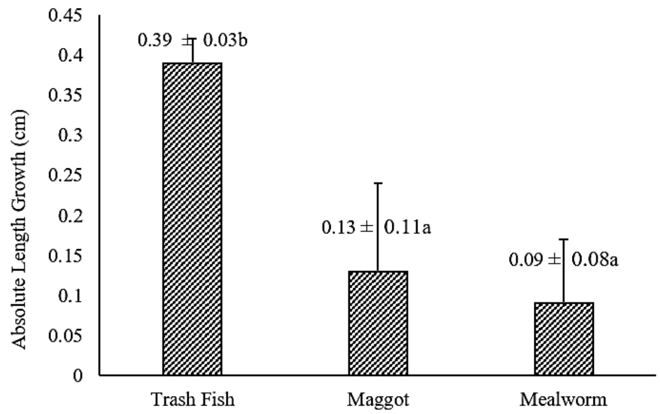

Figure 2. Absolute length growth of spiny lobster (*Panulirus* sp.) under different feeding treatments.

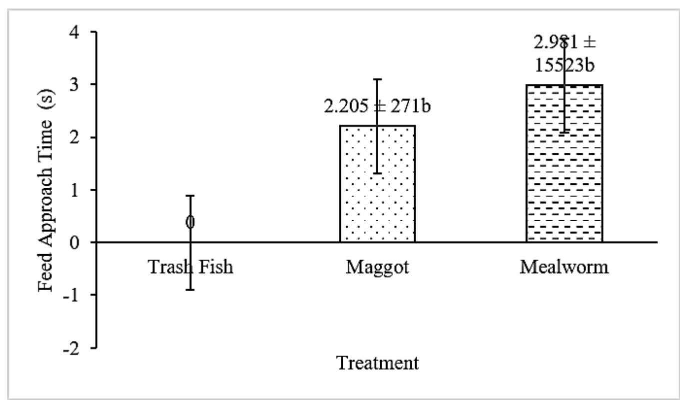

Figure 3. Feed approach time of spiny lobster (*Panulirus* sp.) under different feeding treatments.

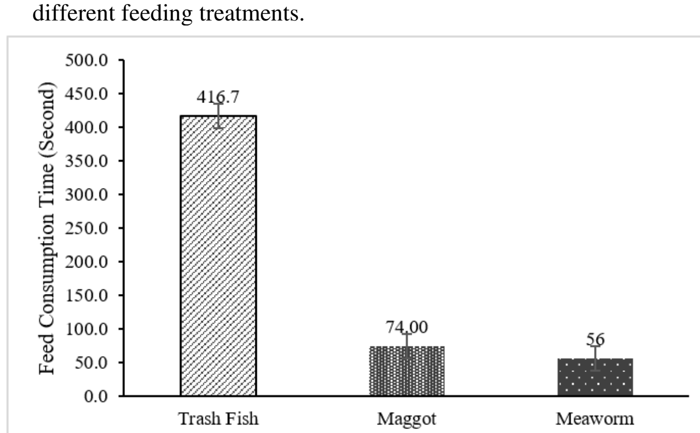

Figure 4. Feed consumption time of spiny lobster (*Panulirus* sp.) under different feeding treatments.

these differences were not pronounced, indicating that

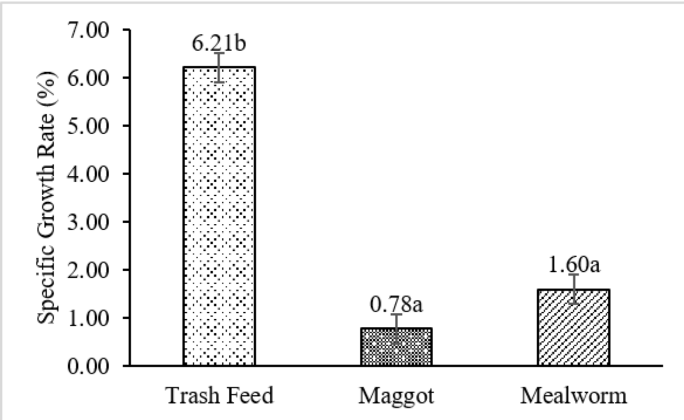

Figure 5. Specific growth rate of spiny lobster (*Panulirus* sp.) under different feeding treatments.

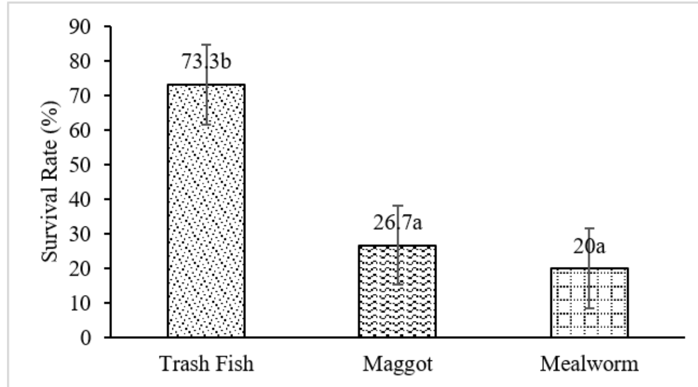

Figure 6. Survival rate of spiny lobster (*Panulirus* sp.) under different feeding treatments.

all feed types were generally acceptable for maintaining lobster survival under controlled conditions (Fig. 6).

Water quality parameters: Water quality parameters remained within acceptable and optimal ranges for spiny lobster culture throughout the experimental period, with no extreme fluctuations among treatments (Table 4). All measured water quality parameters were within optimal or tolerable limits for spiny lobster growth, indicating that environmental conditions did not confound the observed effects of feed treatments on growth and feeding behavior.

Discussions

The present study demonstrates clear differences in growth performance and feeding behavior of spiny lobster (*Panulirus* sp.) in response to different feed types over a 30-day rearing period. Absolute weight growth differed markedly among treatments, with lobsters fed trash fish achieving the highest mean weight gain (6.47 g), followed by mealworms (1.67 g) and Black Soldier Fly (BSF) maggots (0.93 g). This indicates that trash fish remains the most effective feed in promoting short-term biomass accumulation in spiny lobster. Similar trends have been widely reported in lobster growth trials, where fish-based feeds consistently outperform alternative feeds despite the latter being nutritionally adequate (Sudewi et al., 2024; Codabaccus et al., 2025).

The superior growth observed in the trash fish treatment can be attributed primarily to higher palatability, familiarity with the natural diet of spiny lobsters, and more efficient utilization of animal-derived protein and lipids. Spiny lobsters are opportunistic carnivores that naturally consume fish, mollusks, and other benthic organisms rich in animal protein and lipids, which serve as primary energy sources for growth and metabolic processes. Fish-based feeds inherently contain bioactive compounds, essential fatty acids, and balanced amino acid profiles that support efficient nutrient absorption and tissue synthesis, thereby enhancing somatic growth (Astuti et al., 2023; Sudewi et al., 2024). Protein and lipid availability are critical determinants of lobster biomass accumulation. Feeds with high digestibility and appropriate amino acid composition promote muscle development and energy storage, leading to greater weight gain. Although BSF maggots and mealworms possess high crude protein contents, their nutritional bioavailability and amino acid balance may not fully match the specific requirements of *Panulirus* spp. In addition, the presence of chitin in insect exoskeletons may reduce digestibility and nutrient utilization if not properly processed, which could partly explain the lower growth performance observed in insect-based treatments (Nankervis and Jones, 2022; Wang et al., 2024).

Absolute length growth followed the same general trend as weight growth, with trash fish producing the highest increment (0.39 cm), while BSF maggots and mealworms resulted in substantially lower length gains. This consistency suggests a strong relationship between linear growth and biomass increase in spiny lobsters, as previously described in length–weight relationship studies. However, differences in length growth were less pronounced than differences in weight gain, indicating that feed quality exerts a stronger influence on tissue mass deposition than on exoskeletal elongation. This finding is consistent with reports that crustacean length growth is often constrained by molting frequency, whereas weight gain more directly reflects nutrient intake and assimilation efficiency (Sudewi et al., 2021).

Feeding behavior observations further clarify the mechanisms underlying differences in growth among treatments. Feed consumption time varied significantly, with lobsters fed trash fish requiring the longest duration to consume feed (416.7 s), followed by BSF maggots (74.0 s) and mealworms (56.0 s). The prolonged consumption time associated with trash fish likely reflects larger particle size, firmer texture, and the need for extended mechanical processing by lobster mouthparts. Importantly, longer consumption duration does not indicate inefficiency; rather, it suggests sustained feeding activity and prolonged nutrient intake, which can contribute positively to growth performance (Sudewi et al., 2024). In contrast, the shorter consumption times observed for BSF maggots and mealworms indicate easier handling and faster ingestion, but these characteristics did not translate into improved growth. This finding highlights that ease of consumption alone is insufficient to enhance growth if feed intake, palatability, or nutrient utilization remains suboptimal. Similar observations have been reported in crustacean feeding trials, where rapidly consumed feeds did not necessarily result in higher biomass gain due to lower overall intake or reduced digestibility (Astuti et al., 2023).

Feed approach time results further emphasize the importance of palatability and chemical stimulation in lobster feeding. Trash fish elicited the fastest feeding response, confirming its greater attractiveness than insect-based feeds. Spiny lobsters possess highly developed chemosensory systems that enable them to detect amino acids and other soluble compounds released from feed sources. Fish-based feeds naturally release strong olfactory cues that effectively trigger feeding behavior, whereas insect-based feeds may lack sufficient concentrations of these attractants, resulting in slower approach times and reduced feeding enthusiasm (Astuti et al., 2023; Saputra et al., 2024). Prior feeding experience and dietary familiarity also play important roles in shaping lobster feeding responses. Lobsters accustomed to natural or fish-based diets may exhibit neophobic behavior toward novel feeds such as insect-based ingredients, which can suppress initial intake and limit growth, particularly during short experimental periods. Longer adaptation phases or gradual diet transitions may therefore be required to improve acceptance of insect-based feeds in lobster culture systems (Nankervis and Jones, 2022).

Water quality parameters, including temperature (27-29°C), pH (~7.6), salinity (30-35 ppt), and dissolved oxygen (7.1-8.5 mg L^{-1}), remained within optimal ranges for spiny lobster culture throughout the experiment. The absence of extreme fluctuations and the consistency of conditions among treatments indicate that environmental factors did not confound the observed differences in growth and feeding behavior. Consequently, the variations in performance can be attributed primarily to feed type rather than water quality effects.

The findings of this study indicate that while insect-based feeds such as BSF maggots and mealworms possess considerable nutritional potential and sustainability advantages, their effectiveness in promoting lobster growth remains limited when used unmodified. Improving the performance of insect-based feeds will likely require targeted formulation strategies, including incorporating fish or shrimp hydrolysates, adding chemical attractants, fermenting the feed to enhance digestibility, and extending adaptation periods to improve feed acceptance. Such approaches have been shown to enhance palatability, stimulate chemosensory responses, and improve growth outcomes in crustacean aquaculture (Saputra et al., 2024; Sudewi et al., 2024).

From a sustainability perspective, replacing trash fish with optimized insect-based feeds holds substantial promise for reducing pressure on wild fish stocks, improving biosecurity, and supporting circular bioeconomy principles. However, achieving this transition without compromising growth performance requires a deeper understanding of lobster feeding behavior and targeted feed development. The present study contributes to this understanding by demonstrating that growth efficiency in spiny lobster is not solely determined by crude nutritional content but is strongly mediated by palatability, sensory stimulation, and feeding behavior. These insights are critical for guiding future research and the development of sustainable, high-performance feeds for lobster aquaculture.

Conclusion

This study demonstrates that feed type plays a decisive role in determining growth performance and feeding behavior of spiny lobster (*Panulirus* sp.) under controlled culture conditions. Trash fish produced the highest growth efficiency, as reflected by superior weight and length gains, rapid feeding response, and prolonged consumption activity, largely due to higher palatability, dietary familiarity, and effective chemosensory stimulation. In contrast, insect-based feeds derived from Black Soldier Fly maggots and mealworms, while nutritionally rich and environmentally sustainable, resulted in lower growth performance and reduced feeding responsiveness when used as direct feed substitutes. These outcomes indicate that nutritional adequacy alone is insufficient to ensure optimal growth in spiny lobsters; behavioral factors such as feed attractiveness, texture, and acceptance are equally critical. Nevertheless, the positive growth and survival observed in insect-based treatments highlight their potential as sustainable feed resources if appropriately optimized. Future development of insect-based feeds should focus on formulation improvements, including incorporating natural attractants, hydrolysates, or fermentation products, as well as longer adaptation periods to enhance feed acceptance. Overall, this study provides important empirical evidence supporting the transition to more sustainable feeding strategies in lobster aquaculture, while emphasizing the need for behavior-oriented feed design to achieve performance comparable to that of traditional trash fish diets.

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