

ACCEPTED AUTHOR VERSION OF THE MANUSCRIPT:

Harnessing black soldier fly (*Hermetia illucens*) larvae meal for crustacean feed: A review of advances, challenges and future trends

DOI: 10.2478/aoas-2025-0126

Divya Karthick Rajan¹, Durairaj Karthick Rajan^{1♦}, Nagarajan Revathi², Shubing Zhang¹, Kannan Mohan^{2♦}

¹Department of Cell Biology, School of Life Sciences, Central South University, Changsha, Hunan Province, 410013 P.R. China

²PG and Research Department of Zoology, Sri Vasavi College, Erode, Tamil Nadu 638316, India

♦Corresponding author: karthickrajan.d@gmail.com, kmohanphd@gmail.com

Received date: 24 August 2025

Accepted date: 30 October 2025

To cite this article: (2026). Karthick Rajan D., Karthick Rajan D., Revathi N., Zhang S., Mohan K. (2026). Harnessing black soldier fly (*Hermetia illucens*) larvae meal for crustacean feed: A review of advances, challenges and future trends, Annals of Animal Science, DOI: 10.2478/aoas-2025-0126

This is unedited PDF of peer-reviewed and accepted manuscript. Copyediting, typesetting, and review of the manuscript may affect the content, so this provisional version can differ from the final version.

Harnessing black soldier fly (*Hermetia illucens*) larvae meal for crustacean feed: A review of advances, challenges and future trends

Divya Karthick Rajan¹, Durairaj Karthick Rajan^{1♦}, Nagarajan Revathi², Shubing Zhang¹, Kannan Mohan^{2♦}

¹Department of Cell Biology, School of Life Sciences, Central South University, Changsha, Hunan Province, 410013 P.R. China

²PG and Research Department of Zoology, Sri Vasavi College, Erode, Tamil Nadu 638316, India

♦Corresponding authors: karthickrajan.d@gmail.com, kmohanphd@gmail.com

Abstract

Black soldier fly larvae (BSFL) meal is a sustainable aquafeed protein source for crustaceans such as shrimp, crabs, and lobsters. The BSFL meal is high in protein (35–60%), lipids (17–49%), antimicrobial peptides, bioactive substances and biopolymer chitin. The use of BSFL meal in crustacean aquaculture has several benefits, including replacing fishmeal (FM), reducing feed cost, and having no adverse environmental impacts. A variety of factors, including rearing technology, optimization of substrate, and processing methods, were found to influence the nutrient profile and digestibility of crustaceans. In addition, growth performance, feed conversion, immunity, and disease resistance of crustacean species were reported, when fishmeal was partially or completely replaced in their diets. The feed safety regulations, microbial contamination, heavy metal load, variations in proximate composition, and varying levels of amino acids across larval stages were considered as major obstacles. Further, the economic feasibility of insect-derived feeds also depends upon consumer acceptability and the production of insect-based feeds on a large scale. However, future research investigations should focus on replacing insufficient nutrients, improving processing, and conducting long-term feeding experiments. Incorporating BSFL feed into crustacean aquaculture could substantially promote circular bioeconomy goals while improving industrial resilience.

Key words: black soldier fly larvae, crustacean aquaculture, feed ingredient, protein source, nutritional value, sustainability

Aquaculture is one of the fastest-growing industries which helps to meet the increasing demand for seafood (Mohan et al., 2022 a). Global aquaculture production contributed 122.6 million tons in 2020 (FAO, 2022). A variety of fish, shellfish, and seaweed species have been cultured for their nutritional and economic value. Among other organisms, fish and shellfish are cultured predominantly for their food value. In addition, China, India, Indonesia, Vietnam and Bangladesh are considered the largest and dominating aquaculture producers in Asia (Jolly et al., 2023). Most importantly, aquaculture is one of the significant income-generating sectors in many developing and developed nations. Aquaculture production will need to reach 231 million tons by 2050 to reduce the global market demand (Kearney, 2010).

The global crustacean aquaculture industry has achieved a market value of USD 81.5 billion, with a total production volume of 11.2 million metric tons (FAO, 2022). The crustacean farming including shrimp, crab and lobster is rising faster (Boenish et al., 2022). In the crustacean seafood industry, shrimp is expected to dominate in 2023, and reaching 5.7% annually (Villarreal, 2023). Emergence of disease outbreaks, including WSSV, baculovirus,

and yellow head disease, poses a major threat to crustacean farming (Lee et al., 2025; Munro and Owens, 2007; Rajan et al., 2000). Both wild catch and farmed crustacean production reached 10 million metric tons per annum (Stentiford et al., 2012).

Previous studies reported that the cost increase is one of the main reasons hindering aquaculture development (Alfiko et al., 2022). Research evidence highlights that the scarcity of fish feed stocks is another issue that is forcing the aquaculture sector to search for alternative feed sources (Olsen and Hasan, 2012). Large quantities of feeds are required with high nutritional value to improve the growth of targeted organisms in aquaculture. However, researchers are engaged in formulating novel feeds by replacing them with plant, animal and insect proteins. There are several research investigations that highlight the usage of insect-based feeds in aquaculture (Henry et al., 2022; Ge et al., 2022). For instance, a wide range of insect species were utilized for partial and complete feed replacement in the aquaculture sector (Fantatto et al., 2024). Earlier studies demonstrated that various insect species like superworm (*Zophobas morio*), yellow mealworm (*Tenebrio molitor*) and black soldier fly (*Hermetia illucens*) serve as a good source of protein (Richardson et al., 2021; Henry et al., 2022; Ge et al., 2022). Mainly, insects comprise 60–70% of protein, and they can serve as an alternative feed for aquatic organisms (Udomsil et al., 2019; Stamer, 2015).

Likewise, BSFL is not only a rich source of protein (Richardson et al., 2021). Nevertheless, it also serves as a good source of amino acids and fatty acids (Zulkifli et al., 2022). Preparation and utilization of BSFL-based feeds in the aquaculture sector is rising steadily. For instance, the role of BSFL feed in fish aquaculture has been reviewed previously (Mohan et al., 2022 a). Many studies have proven that BSFL feeds can improve the growth and immunity of aquacultural crustaceans. The use of BSFL in crustacean feed lies in its sustainable, protein-rich, and cost-effective nature. BSFL serves as an excellent alternative to fishmeal, reducing dependence on marine resources. It enhances growth performance, immunity, and feed conversion efficiency in crustaceans. Moreover, black soldier fly cultivation supports waste recycling and circular bioeconomy practices. However, there is no detailed review stating the role and limitations of BSFL in crustacean aquaculture. Hence, this review aims to highlight the role of BSFL in crustacean aquaculture. The review further examines the key challenges, and possible future prospects.

Nutritional profiles of BSFL

Body composition

BSFL serves as an exceptional source of crude protein, fat, and ash contents. Specifically, lauric acid, a type of fatty acid, is also present in BSFL (Ewald et al., 2020). Studies demonstrated that the black soldier fly proximate composition varies among different stages and the diet used for rearing (Khan et al., 2025). Previous studies suggested that the rearing substrate can influence the amino acid, protein and fatty acid contents of BSFL (Fitriana et al., 2022). Different substrates provide varying nutrient profiles that directly influence amino acid balance, protein levels, and fatty acid composition. Protein-rich substrates enhance the essential amino acid content and overall protein yield (Fitriana et al., 2022). Conversely, lipid-rich substrates promote larval fat accumulation, improving lipid yield for biofuel or feed applications. However, excessively high lipid levels may reduce substrate aeration and impair larval growth efficiency (Cattaneo et al., 2023). Therefore, optimizing substrate composition is essential to produce BSFL with desirable nutritional qualities for feed applications. The BSFL were recognized as nutrition-rich stages (Hui et al., 2009). Furthermore, minerals and chitin were also reported from BSFL. It is noteworthy to mention that BSFL have an essential nutritional composition for producing poultry or aquatic feed (Moula et al., 2018). However, clearer information on different stages of body proximate composition would pave the path for outstanding novel feed formulations for aquaculture.

Protein/amino acid content

BSFL contains about 40–45% of crude protein and is rich in essential amino acids (Zheng et al., 2012; Liu et al., 2024). It provides a sustainable alternative protein source for aquaculture. Huseynli et al. (2023) reported that the dry matter of BSFL contains 30 to 53 g/100 g of protein. The freeze-dried BSFL sample contains 30.12 g/100 grams of crude protein, as reported earlier (Miron et al., 2023). Likewise, Lu et al. (2022) reported a BSFL crude protein concentration of 414.7 g/kg. The essential amino acids, including arginine, glutamic acid, aspartic acid, proline, serine, valine, leucine, tyrosine, glycine, and lysine, were reported in BSFL (Zulkifli et al., 2022; Miron et al., 2023). Meanwhile, the quantity of amino acids can vary among different larval stages and feeds utilized in rearing the BSFL (Dillard et al., 2025). BSFL reared using different wastes was found to exhibit a sufficient quantity of protein and amino acids, ensuring that it can be utilized for partial or complete crustacean meal replacement.

Fatty acid content

BSFL fat contains saturated fatty acids and polyunsaturated fatty acids. Specifically, lauric acid, palmitic acid, and arachidonic acid were reported from different stages of BSFL (Ewald et al., 2020). Lee et al. (2025) mentioned the composition of fatty acids from BSFL. Lauric acid is the predominant medium-chain fatty acid in BSFL, known for its strong antimicrobial properties. It enhances feed quality and promotes gut health in aquatic species. Ewald et al. (2020) reported that lauric acid is the major saturated fatty acid in BSFL, with levels up to 52%. In another study, Fitriana et al. (2022) reported 36.74% of lauric acid from BSFL (Fitriana et al., 2022). Further, BSFL comprised 85.6% of saturated fatty acids and 14.4% of unsaturated fatty acids. In another study, Srisuksai et al. (2024) confirmed the presence of fatty acids in the BSFL oil. Recently, Gatlin III et al. (2024) reported the presence of fatty acid compositions using GC-MS analysis. Furthermore, DHA (docosahexaenoic acid) and EPA (eicosapentaenoic acid) in diets are important for the growth and survival of crustaceans. For instance, a previous study demonstrated that diets containing DHA and EPA levels of 0.70 and 0.84 in the crab diet improved growth and survival rates in *Portunus trituberculatus* (Hu et al., 2017). Jiang et al. (2022) reported that DHA is an important fatty acid for ovarian development in *Eriocheir sinensis*.

Mineral contents

Minerals play an important role in crustacean's skeletal formation (Muralisankar et al., 2022). The requirements of minerals vary based on the different developmental stages (Truong et al., 2023). Previous findings reported the effects of 12 different minerals on diet using *P. monodon* juveniles (Truong et al., 2020). BSFL are rich in essential minerals, including calcium, phosphorus, magnesium, potassium, and sodium, as well as trace elements such as iron, zinc, and manganese. Their exceptionally high calcium-to-phosphorus ratio makes them valuable for animal feed, especially in aquaculture. A study reported that BSFL reared on fruit peels can improve Ca, K, P, and Mg concentrations (Romano et al., 2023). A study documented that calcium (Ca) was predominantly present in the BSFL (Zulkifli et al., 2022). Previous findings stated that BSFL could serve as a good source of mineral contents (Kouřimská and Adámková, 2016). A study stated that the quality of calcium ranges from 1.2 g/kg to 35.7 g/kg (Lu et al., 2022). Meanwhile, the role of minerals in crustacean species is not clearly explored. However, additional investigation on BSFL mineral content will pave a way to improve the feed formulation and their impacts in crustacean culture.

Chitin content

Chitin is a natural biopolymer, reported in crustaceans, fungi, molluscs, insects (Mohan et al., 2019; Zainol Abidin et al., 2020; Mohan et al., 2020, 2021; Iber et al., 2022; Karthick

Rajan et al., 2024). Chitin can be extracted from various natural resources via chemical and greener approaches (El Knidri et al., 2018; Maddaloni et al., 2020; Mohan et al., 2022 b). Among them, the greener approach is gaining importance for its eco-friendly properties. Mohan et al. (2024) reported that BSFL serves as a good source of chitin and chitosan and is used for various applications. Chitin yield was reported as 200 g kg⁻¹ from BSFL and 155 g kg⁻¹ from *T. molitor* larvae (Hahn et al., 2018). Previous findings have shown that an excess of chitin in the aquaculture diet can negatively affect lipid and protein digestibility (Marono et al., 2015; Pascon et al., 2025). On the other hand, chitin present in insect meal may exhibit negative impact on nutrient availability and affect the fish performance (Rangel et al., 2024). Distribution of chitin in different larval stages of BSFL was reported earlier (Wang et al., 2020). Based on the crystalline allomorphs, chitin has been categorized into three different types (α , β , and γ). The chitin found on the BSFL is of the α type, and this type is predominantly present in shrimps and insects. A chitin concentration of 11.78 $\pm$ 0.13% was reported from the prepupae stage after being fed on vegetable wastes (Rampure et al., 2023).

Rearing strategies for black soldier fly

A variety of food and vegetable wastes has been utilized for rearing the BSFL. Different methods have been applied to rear insects, and it has been developed globally (Lähtenmäki-Uutela et al., 2021). Mainly, BSFL was used for the bioconversion of food wastes and considered as an alternative solution to avoid the environmental issues created by food and agriculture wastes (Siddiqui et al., 2022; Rehman et al., 2023; Abirami et al., 2024). The nutritional values of BSFL derived from fruit and vegetable wastes were reported previously (Deshmukh et al., 2024). Likewise, BSFL reared using fermented coconut endosperm waste enhanced the lipid and protein profile of BSFL (Mohd-Noor et al., 2017). Rasdi et al. (2023) evaluated the rearing efficiency of BSFL using different agricultural wastes. Fischer and Romano (2021) reported that BSFL reared using a vegetable waste source have higher amino acid levels and protein content. Yandi et al. (2023) reported that chicken, fruit and vegetable mixed waste sources can be used to rear BSFL and could be used to replace the fish meal partially. Overall, previous literature reviews demonstrated that BSFL can grow in various organic wastes (Rampure et al., 2023; Mohan et al., 2024). On the other hand, the rearing medium used for culturing the BSFL has certain limitations, including pathogenic microbial communities, foul odor and more chances for heavy metal contamination. Hence, it would be better to analyze or evaluate the substrate to avoid the risks.

BSFL meal as a feed ingredient for crustacean aquaculture

BSFL meal is a sustainable alternative protein source for crustacean aquaculture, reducing reliance on fishmeal. It enhances growth performance, immunity, and feed efficiency while supporting eco-friendly farming practices (Figure 1; Table 1).

Pacific white shrimp (*Litopenaeus vannamei*)

The shrimp species *L. vannamei*, also known as the Pacific white leg shrimp, has gained special attention for its nutritional value (Cuzon et al., 2004). Consequently, its global market value is anticipated to grow every year. In this context, BSFL feed presents a potential role in the aquaculture sector, although there are some limitations. For example, Yildirim-Aksoy et al. (2022) described that *L. vannamei* fed with different (0, 5, 10, 20, and 30%) levels of BSFL meal for 12 weeks significantly increased in weight. Notably, among the tested concentrations, a 20% inclusion level also developed resistance against the pathogenic *Vibrio parahaemolyticus*. On the contrary, *L. vannamei* supplemented with 10% and 20% of BSFL meal for 7 weeks displayed no significant improvement in terms of growth and lipid content, which were found to be reduced. However, total antioxidant and SOD enzymes were elevated

(Chen et al., 2023 a). Additionally, *L. vannamei* diets containing 1, 1.5 and 2% BSFL meal supplementation for 42 days affected total feed consumption and feed utilization (Herawati et al., 2024). A study conducted by He et al. (2024) revealed that shrimp diets containing 75% and 100% of BSFL meal improved the weight gain, fatty acid content, and lipid synthesis in *L. vannamei*. Further, BSFL meal upregulated the immune-related mRNA expressions in *L. vannamei*. In another study, *L. vannamei* fed with BSFL meal for 28 days showed decreased growth rate (Li et al., 2022). Furthermore, BSFL meal incorporated diet supplemented for 45 days improved survival rate, body weight, and displayed higher hepatopancreas enzyme activity on *L. vannamei* (He et al., 2022). In another finding, Herawati et al. (2023) described that BSFL diet supplementation enhanced the fatty acid as well as amino acid content in *L. vannamei*. A 45-day trial conducted using BSFL diet on *L. vannamei* revealed that SOD and phenol oxidase activities were found to be increased (Shin et al., 2021). A study conducted by He et al. (2022) evidenced that 75% and 100% BSFL diets significantly improved the hepatosomatic index and protease activity, whereas a reduction in intestinal fold height was also observed. Nunes et al. (2023) studied shrimp diets containing graded concentrations (0, 25, 50, 75, and 100%) of BSFL diets. Among the tested diets, shrimp fed using 0% and 100% of BSFL displayed highest FCR values of 1.25 ± 0.04 and 1.24 ± 0.08 , respectively when compared with 50% diet. Notably, BSFL feed incorporated with different levels (10, 20, and 30%) evidenced that mRNA levels of antimicrobial peptides-related genes were upregulated, whereas mRNA levels of non-specific immune genes were downregulated (Chen et al., 2021). In another investigation, *L. vannamei* fed with BSFL incorporated meal for 45 days increased alkaline phosphatase, acid phosphatase, and nitric oxide, followed by a decrease in hepatopancreas activity (He et al., 2022). Fricke et al. (2024) reported that different stages of BSFL feed supplements increased the digestibility. Shin et al. (2021) documented the effects of various insect-based diets, and results revealed that insect-based diets can promote the growth, antioxidant enzymes, and immune response of shrimp *L. vannamei*. Terrey et al. (2021) reported that 1% and 2% diets incorporating BSFL improved palatability potential and the amino acid profile. In another study, BSFL meal diets supplemented for 60 days were found to reduce the amino acid, lipid, and collagen content in flesh (Zheng et al., 2024). A BSFL diet at 0.5% to 5% supplementation for 90 days was found to enhance feed utilization and growth performance (Novriadi et al., 2023). Most importantly, the 40% and 60% BSFL meal incorporated diet improved feed efficiency and growth rate. In addition, it was also found to enhance the enzyme levels and immune gene crustin (Shin et al., 2020). Contrary results were observed in *L. vannamei* supplemented with different inclusion levels of BSFL after 60 days (Chen et al., 2023 b). Whereas, Fahrur et al. (2021) reported that no improvement in terms of growth, survival, and weight was observed after 49 days of BSFL diet supplementation in *L. vannamei*. Similarly, Wang et al. (2021) reported that reduced specific growth rate (SGR) and body weight were observed in *L. vannamei* supplemented with BSFL diet. Further, antioxidant levels and higher FCR were also noticed after 56 days. Different inclusion levels (0–30%) of BSFL-based diet supplemented for 8 weeks improved the SGR and weight gain rate of *L. vannamei*, and increased calcium content was also observed (Hu et al., 2019). Among the tested concentrations, a concentration of 80% BSFL diet improved the SGR, weight gain, and enhanced enzyme activities. Further, the group supplemented with a maximum concentration of 100% BSFL exhibited a lower survival rate (Ming et al., 2024). In particular, different levels of BSFL (10%, 20% and 30%) meal incorporated diets supplemented to *L. vannamei* for 7 weeks decreased the growth performance and lipid contents. Further, no changes in survival rate were also observed (Chen et al., 2022). Keetanon et al. (2024) reported that diets incorporated with various concentrations of BSFL improved body weight, and immune status, followed by a decrease in hepatopancreatic activity and intestinal *Vibrio* spp. counts. Recently, Chang et al. (2025) demonstrated that a BSFL diet supplemented to *L.*

vannamei for 8 weeks did not alter the growth performance, reducing the intestinal inflammation and boosting the antioxidant and immune status, respectively. Some of the studies pointed out that the BSFL feed incorporated diets significantly affect the growth rates, and the reason remains unclear. But overall, all the findings reported earlier were not similar, and a deeper analysis is required, and more studies related to detailed investigations of growth-related genes will pave the path for understanding growth rates.

Giant freshwater prawn (*Macrobrachium rosenbergii*)

The freshwater prawn *Macrobrachium rosenbergii* is cultured for its high nutritional value. It has been considered an economically important freshwater prawn species. There is a steady increase in use of BSFL meal for partial or complete feed replacement in fish and finfish aquaculture. For instance, McCallum et al. (2020) documented that BSFL meal supplementation for 1 week improved the growth performance of *M. rosenbergii*. Likewise, *M. rosenbergii* fed with different percentages (15, 30, and 45%) of BSFL meal significantly increased the growth and survival rate (Raja Hishamudin, 2020). In another study, *M. rosenbergii* supplemented with 5, 10 and 15% of BSFL meal improved the protein digestibility (Harun et al., 2021). Furthermore, a significant increase in protein and lipid content, and improved protein digestibility were observed in *M. rosenbergii* fed with 5, 10, and 15% of BSFL meal (Amiruddin et al., 2021). In another study, Zarantoniello et al. (2023) reported that α -tocopherol and carotenoid contents were found to be increased after being supplemented with 3 or 20% BSFL meal for 60 days. Further, the study also highlighted that BSFL meal diets did not affect the immune expression and stress-related markers. However, few research studies have investigated the role of BSFL diets using *M. rosenbergii*. Hence, it is recommended to investigate the growth-related and immune-related genes, followed by enzyme levels in the near future.

Lobster

Lobster is a high-protein, low-fat food rich in several essential vitamins and minerals, including selenium, zinc, copper, and vitamin B₁₂, as well as omega-3 fatty acids (Barrento et al., 2009). Hinchcliffe et al. (2022) reported the challenges involved in lobster, *Homarus gammarus* culture. Lobster meal is a protein-rich by-product from lobster processing, used as a sustainable ingredient in aquaculture feeds. It enhances growth, feed efficiency, and nutritional quality of aquaculture. *Homarus gammarus* was fed with BSFL up to 15% and it showed elevated body glycogen content, increased exo- and endochitinase activity (Goncalves et al., 2024). Likewise, in the initial stage of 0.24 g weight *Panulirus ornatus* was fed with BSFL around 25% in the overall feed for 56 days exposure and it showed increased ash and protein contents, high total contents of monounsaturated fatty acids, saturated fatty acids, omega-9 fatty acids, villus size, muscle thickness in the intestine was also not affected, and improvements in the growth rate, final body weight, final total length and length increment were also noticed (Saputra et al., 2024). Similarly, *P. ornatus* was fed with 0, 25, 35 and 50% of BSFL, which helped to reduce the dry matter loss of the feed at high salinity (Saputra and Fotedar, 2023). Recently, *P. ornatus* at initial weight of 0.24 g was fed with 0, 25, 35 and 50% of BSFL at 56 days, which did not alter the whole-body proximate composition, significantly affected the superoxide dismutase, increased the inflammatory cytokine cells; no difference was observed in final weight, specific growth rate, length size, survival rate, molting rate and molt interval (Saputra and Fotedar, 2024).

Crayfish

The crayfish aquaculture is one of the rapidly growing industries. Crayfish species are found in both freshwater and saltwater habitats and are consumed especially for their vitamin

and mineral content (El-Sherif et al., 2021). BSFL meals with 0 and 12% inclusion levels fed to freshwater crayfish *Cherax cainii* improved the immune status, intestinal microbes, and hemolymph parameters (Foysal et al., 2021). In another investigation, Foysal et al. (2019) reported that BSFL meal supplemented to *C. cainii* for 60 days improved the hemolymph enzyme levels and THC. A previous report suggested that a BSFL meal supplemented to *Pontastacus leptodactylus* diets for 60 days improved the survival rate and weight gain (Koca et al., 2024). Additionally, a study conducted by Alvanou et al. (2023) reported that different inclusion levels (0, 50, and 100%) of BSFL incorporated diet improved the survival rate percentage (SRP), SGR, weight gain, and enhanced the body proximate composition of *P. leptodactylus*. Similarly, different concentrations of BSFL meal supplemented to *P. leptodactylus* improved the SGR and weight gain (Özdoğan et al., 2024). Recently, Chu and Huang (2024) highlighted that a BSFL meal supplement for *Cherax quadricarinatus* for 56 days improved the growth rate, enhanced immunity, and improved digestibility. Most importantly, feed incorporated with 0, 50, 100, 150, and 200 mg/kg of crude peptide extracts for 56 days increased the immunity and antioxidant response (Zhang et al., 2024). Similarly, Wang et al. (2024) investigated the effects of different concentrations of BSFL diet supplementation using *C. quadricarinatus*, and the results showed positive effects on crayfish. In contrast, Subchan et al. (2024) reported that a BSFL diet supplemented to *C. quadricarinatus* for 28 days did not result in improved growth rate and a low FCR. Han et al. (2023) reported the effects of BSFL diet supplementation using *Procambarus clarkii*, and the results revealed that the BSFL meal can improve the enzyme levels, protein content, and final body weight.

Crab

A limited number of crustacean species have been reared for their market value. *Portunus pelagicus* is one of the commercially important crab varieties reared for their nutritional values (Fujaya et al., 2016). Syafaat et al. (2021) documented the fundamentals of *Scylla serrata* farming. BSFL at various concentrations (0, 25, 50, 75, 100%) was fed with initial stage of 7.15 g weight of *Eriocheir sinensis* at 56 days, and it showed increased final weight, weight gain, feed conversion ratio, increased survival (25% and 50%), immune enzyme activity, acid phosphatase, alkaline phosphatase and lysozyme activity; no significant differences were observed in antioxidant activity, total antioxidant capacity, superoxide dismutase, glutathione peroxidase activities (25% and 50%), high level of intestinal number of folds and folds height (25% and 50%) (Yao et al., 2024). Similarly, *Scylla paramamosain* with initial weight of 1.43 g was fed with BSFL at various concentrations (0, 5, 10 and 15%); with replacement of 10% for 56 days, it showed highest weight growth rate and specific growth rate (10%), and slightly increased crude protein content and activities of amylase, protease and lipase, higher lipid content (5%) were noticed (Yang et al., 2023). Also, *S. paramamosain* with initial weight of 5.2 g was fed with BSFL at various concentrations (0, 25, 50 and 75%) with replacement of 25% ~50% for 28 days; it showed significantly increased body length, body width and body weight of crabs (25% and 50%), increased body height of crabs, reduced cysteine content of crab body (75%), decreased PUFA and PUFA (n-3) in crab body (75%) (Zhang et al., 2023). Furthermore, *E. sinensis* with initial weight of 0.7 g was fed with BSFL at various concentrations (0, 10, 20, 30, 40, 50%) with replacement of 50% for 56 days and it showed decreased weight gain and specific growth rate (50%), lower total antioxidant capacity (50%), lower activities of antioxidant enzymes (30, 40 and 50%), without affecting the weight gain rate, specific growth rate, the relative expression of genes related to the nonspecific immunity, deformed hepatopancreas (50%) (Wang et al., 2024).

Negative impacts of BSFL meal on crustacean feed

Few studies have reported that the inclusion of BSFL meal in crustacean diet can pose negative impacts on growth performance and feed utilization, especially at higher inclusion levels or under suboptimal processing conditions (Cummins et al., 2017; Wang et al., 2021, 2024; Chen et al., 2022, 2023 a; Li et al., 2022; Zhang et al., 2024). Furthermore, excessive BSFL meal replacement (above 20–30%) often resulted in reduced feed intake, poor growth performance, and a lower FCR due to imbalanced amino acid profiles (especially low methionine and lysine) or due to high chitin content and lower palatability (Cummins et al., 2017; Wang et al., 2021). Zulkifli et al. (2022) stated that inadequate processing methods, including improper drying or the lack of fermentation, can also decrease protein digestibility and increase the presence of antinutritional factors. Similarly, the use of full-fat BSFL meal may elevate lipid oxidation and reduce feed stability, whereas defatted forms may improve digestibility but alter energy balance (Ko et al., 2025). Moreover, the larval developmental stage significantly affects nutritional composition; older larvae tend to accumulate more chitin and saturated fats, reducing digestibility compared to younger instars (Rangel et al., 2024). These are some of the main factors that led to contradictory results and negative impacts across studies evaluating the inclusion of BSFL in crustacean feeds.

Feed safety regulation for using BSFL in crustacean aquaculture

In the European Union (EU), BSFL have been legally authorized for incorporation into aquaculture feeds since July 1, 2017. These are governed by Commission Regulation 2017/893, which allows insects, such as BSFL, to be utilized as sources of processed animal protein, provided they are raised on substrates that adhere to EU regulations (e.g., excluding catering waste, manure, or unapproved animal by-products) and comply with the Animal By-Products Regulation (EU No 1069/2009). Similar to the USA, BSFL is permitted under the Generally Recognized as Safe (GRAS) framework; however, producers are required to confirm the safety of the contaminants and adhere to both federal and state regulations. The safety of BSFL rearing is fundamentally dependent on the substrates utilized (Tariq et al., 2025). EU regulations restrict substrates to those derived from vegetable sources or specific approved animal-origin materials, explicitly prohibiting manure and catering waste. According to research, depending on the diet content, BSFL can bioaccumulate heavy metals, particularly cadmium, lead, arsenic, and mercury (Wu et al., 2020). Certain bioaccumulation factors are higher than 1, especially for cadmium and mercury. Furthermore, BSFL may contain allergenic proteins, such as tropomyosin and arginine kinase, which can cross-react with allergies to crustaceans (Delfino et al., 2024). The Singapore Food Agency (SFA) permits the use of BSFL in aquafeed under strict safety regulations, ensuring they are reared on approved substrates and processed hygienically. These guidelines aim to prevent contamination and ensure feed quality for crustacean aquaculture. In many other Asian countries there is no specific feed-ingredient regulation for insects (or BSFL) in aquaculture or crustacean feed.

Challenges of using BSFL in crustacean aquaculture

The inclusion of BSFL as a sustainable protein source in crustacean aquaculture raises various nutritional challenges (Dîrvariu et al., 2025). Despite being high in protein, BSFL meal's amino acid composition might not entirely meet the unique needs of crustaceans, such as shrimp and crabs, which could cause growth and health problems if it is not complemented with other protein sources. BSFL has chitin in its exoskeleton, which may impair nutrient digestibility in certain species, especially during early developmental stages when digestive enzymes are reduced (Eggink et al., 2022). This requires the application of processing techniques or enzyme additives to enhance bioavailability. Economic and processing limitations prevent broad application. For successful large-scale commercialization, BSFL

rearing requires good quality control strategies, a complete drying and defatting process to minimize spoilage and preserve nutritional quality (Oh et al., 2024). The processing steps may elevate production costs, potentially reducing the competitiveness of BSFL relative to conventional fishmeal in specific markets. Moreover, the variations in larval rearing substrate can negatively affect the nutritional composition of BSFL, which may result in poor or inconsistent feed quality, and which is not recommended for healthy aquaculture practice (Ribeiro et al., 2022). Moreover, the use of insect-based feeds in crustacean farming may progress slowly due to a lack of awareness among both farmers and consumers. Resolving these issues is crucial prior to the widespread integration of BSFL into crustacean aquaculture diets.

Conclusions and future trends

BSFL represents a viable, sustainable ingredient for crustacean feed, characterized by high protein content, a desirable amino acid profile, and beneficial bioactive compounds. Research indicates that substituting conventional protein sources, including fishmeal, with BSFL can yield similar or enhanced growth performance, feed conversion efficiency, and health in different crustacean species. Furthermore, the production of BSFL uses organic waste streams, thereby supporting circular economy objectives and limiting environmental impact. Challenges persist in the large-scale acceptance of this approach, notably in optimizing nutrient digestibility, balancing chitin levels, standardizing rearing substrates, and maintaining cost competitiveness with conventional feed ingredients. Future trends indicate a focus on improving processing methods to increase digestibility and palatability, potentially utilizing enzymatic or microbial treatments. Improvements in genetic selection and automation within insect farming may enhance yield consistency and quality. Investigating the functional properties of BSFL, including its immunostimulatory and antimicrobial effects, could enhance its application beyond nutrition into health management. Market penetration will also be influenced by regulatory frameworks and the acceptance of the product by consumers. In summary, ongoing innovation and incorporation into sustainable aquaculture practices indicate BSFL as a promising and environmentally friendly protein source for crustacean farming.

Acknowledgements

The author KM expresses his sincere gratitude to the Department of Zoology, Sri Vasavi College, Erode, Tamilnadu, India for providing necessary facilities for the preparation of review.

References

- Abirami A.G., Mohan K., Kandasamy S., Surendran R.P., Kumar R., Rajan D.K., Rajarajeswaran J. (2024). Food waste-derived black soldier fly (*Hermetia illucens*) larval resource recovery: A circular bioeconomy approach. *Process Saf. Environ. Prot.*, 184: 170–189.
- Alfiko Y., Xie D., Astuti R.T., Wong J., Wang L. (2022). Insects as a feed ingredient for fish culture: Status and trends. *Aquac. Fish.*, 7: 166–178.
- Alvanou M.V., Kyriakoudi A., Makri V., Lattos A., Feidantsis, K. Papadopoulos D.K., Georgoulis I., Apostolidis A.P., Michaelidis B., Mourtzinis I., Asimaki A. (2023). Effects of dietary substitution of fishmeal by black soldier fly (*Hermetia illucens*) meal on growth performance, whole-body chemical composition, and fatty acid profile of *Pontastacus leptodactylus* juveniles. *Front. Physiol.*, 14: 1156394.
- Amiruddin W.M., Sofia A.S.Z., Al-Amsyar S.M., Rusli N.D., Mat K.B., Sukri S.M. Mohd M., Harun H.C. (2021). Pre-treatment of black soldier fly larvae (BSFL) using neutral salt

- to improve protein digestibility of *Macrobrachium rosenbergii* feed. In IOP Conference Series: Earth and Environmental Science, IOP Publishing, pp. 012071.
- Barrento S., Marques A., Teixeira B., Vaz-Pires P., Nunes M.L. (2009). Nutritional quality of the edible tissues of European lobster *Homarus gammarus* and American lobster *Homarus americanus*. J. Agric. Food Chem., 57: 3645–3652.
- Boenish R., Kritzer J.P., Kleisner K., Steneck R.S., Werner K.M., Zhu W., Schram F., Rader D., Cheung W., Ingles J., Tian Y. (2022). The global rise of crustacean fisheries. Front. Ecol. Environ., 20: 102–110.
- Candela-Maldonado Y., Megder I., Tefal E., Peñaranda D.S., Martínez-Llorens S., Tomás-Vidal A., Jover-Cerdá M., Jauralde I. (2025). Four organic protein source alternatives to fish meal for Pacific white shrimp (*Penaeus vannamei*) feeding. Fishes, 10: 384.
- Cattaneo A., Meneguz M., Dabbou S. (2023). The fatty acid composition of black soldier fly larvae: the influence of feed substrate and applications in the feed industry. J. Insects Food Feed., 10: 533–558.
- Chang T., Lin H., Han F., Xu C., Li E. (2025). Impact of defatted black soldier fly (*Hermetia illucens*) larvae meal on health, muscle texture, and intestinal microbiota in Pacific white shrimp (*Penaeus vannamei*). Aquaculture, 596: 741755.
- Chen Y., Chi S., Zhang S., Dong X., Yang Q., Liu H., Tan B., Xie S. (2021). Evaluation of the dietary black soldier fly larvae meal (*Hermetia illucens*) on growth performance, intestinal health, and disease resistance to *Vibrio parahaemolyticus* of the Pacific white shrimp (*Litopenaeus vannamei*). Front. Mar. Sci., 8: 706463.
- Chen Y., Chi S., Zhang S., Dong X., Yang Q., Liu H., Tan B., Xie S. (2022). Effect of black soldier fly (*Hermetia illucens*) larvae meal on lipid and glucose metabolism of Pacific white shrimp *Litopenaeus vannamei*. Br. J. Nutr., 128: 1674–1688.
- Chen Y., Zhuang Z., Liu J., Wang Z., Guo Y., Chen A., Chen B., Zhao W., Niu J. (2023 a). Effects of *Hermetia illucens* larvae meal on the Pacific white shrimp (*Litopenaeus vannamei*) revealed by innate immunity and 16S rRNA gene sequencing analysis. Comp. Biochem. Physiol. - D: Genom. Proteom., 46: 101080.
- Chen Y.K., Zheng C.Z., Zhang S., Chi S.Y., Dong X.H., Yang Q.H., Liu H.Y., Tan B.P., Xie S.W. (2023 b). Dietary black soldier fly (*Hermetia illucens*) larvae meal on growth performance, non-specific immunity and lipid metabolism of *Litopenaeus Vannamei*. Acta Hydrobiol. Sin., 47: 269–278.
- Chu J.H., Huang T.W. (2024). Evaluation of black soldier fly larvae meal on growth, body composition, immune responses, and antioxidant capacity of redclaw crayfish (*Cherax quadricarinatus*) juveniles. Animals, 14: 404.
- Cummins Jr V.C., Rawles S.D., Thompson K.R., Velasquez A., Kobayashi Y., Hager J., Webster C.D. (2017). Evaluation of black soldier fly (*Hermetia illucens*) larvae meal as partial or total replacement of marine fish meal in practical diets for Pacific white shrimp (*Litopenaeus vannamei*). Aquaculture, 473: 337–344.
- Cuzon G., Lawrence A., Gaxiola G., Rosas C., Guillaume J. (2004). Nutrition of *Litopenaeus vannamei* reared in tanks or in ponds. Aquaculture, 235: 513–551.
- Delfino D., Prandi B., Ridolo E., Dellafiora L., Pedroni L., Nicoletta F., Cavazzini D., Sforza S., Tedeschi T., Folli C. (2024). Allergenicity of tropomyosin variants identified in the edible insect *Hermetia illucens* (black soldier fly). Food Chem., 437: 137849.
- Deshmukh S.S., Srikanth B.H., Manju G.U., Nandhini D., Revannavar R., Pavana J.K., Pradeep S., Sridhara S. (2024). Nutritional composition of black soldier fly, *Hermetia illucens* (L.) during various life stages reared on vegetable and fruit waste. Entomol. News., 131: 121–128.
- Dillard R.B., Jones M.K., Davis A.J. (2025). Assessing dried black soldier fly larva as a feed component for poultry production. J. Appl. Poultry Res., 34: 100570.

- Dîrvariu L., Barbacariu C.A., Burducea M., Simeanu, D. (2025). Feed sources for sustainable aquaculture: black soldier fly larvae (BSFL). *Fishes*, 10: 464.
- Eggink K.M., Pedersen P.B., Lund I., Dalsgaard J. (2022). Chitin digestibility and intestinal exochitinase activity in Nile tilapia and rainbow trout fed different black soldier fly larvae meal size fractions. *Aquac. Res.*, 53: 5536–5546.
- El Knidri H., Belaabed R., Addaou A., Laajeb A., Lahsini A. (2018). Extraction, chemical modification and characterization of chitin and chitosan. *Int. J. Biol. Macromol.*, 120: 1181–1189.
- El-Sherif A. (2021). Nutritional composition and amino acid profile of the crayfish byproduct meal. *Egypt. J. Aquat. Biol. Fish.*, 25: 909–915.
- Ewald N., Vidakovic A., Langeland M., Kiessling A., Sampels S., Lalander C. (2020). Fatty acid composition of black soldier fly larvae (*Hermetia illucens*) – Possibilities and limitations for modification through diet. *Waste Manag.*, 102: 40–47.
- Fahrur M., Asaad A.I.J., Fahmi M.R. (2021). The utilization of black soldier fly larvae meal as a substitution of fish meal in diet for white shrimp, *Litopenaeus vannamei*, grow-out. In IOP Conference Series: Earth and Environmental Science, IOP Publishing, pp. 012023.
- Fantatto R.R., Mota J., Ligeiro C., Vieira I., Guilgur L.G., Santos M., Murta D. (2024). Exploring sustainable alternatives in aquaculture feeding: the role of insects. *Aquac. Rep.*, 37: 102228.
- FAO (2022). The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation (Rome: FAO).
- Fischer H., Romano N. (2021). Fruit, vegetable, and starch mixtures on the nutritional quality of black soldier fly (*Hermetia illucens*) larvae and resulting frass. *J. Insects Food. Feed.*, 7: 319–327.
- Fitriana E.L., Laconi E.B., Astuti D.A., Jayanegara A. (2022). Effects of various organic substrates on growth performance and nutrient composition of black soldier fly larvae: A meta-analysis. *Biores. Technol. Rep.*, 18: 101061.
- Foysal M.J., Fotedar R., Tay C.Y., Gupta S.K. (2019). Dietary supplementation of black soldier fly (*Hermetica illucens*) meal modulates gut microbiota, innate immune response and health status of marron (*Cherax cainii*, Austin 2002) fed poultry-by-product and fishmeal based diets. *PeerJ*, 7: e6891.
- Foysal M.J., Fotedar R., Siddik M.A., Chaklader M.R., Tay A. (2021). *Lactobacillus plantarum* in black soldier fly (*Hermetica illucens*) meal modulates gut health and immunity of freshwater crayfish (*Cherax cainii*). *Fish Shellfish Immunol.*, 108: 42–52.
- Fricke E., Saborowski R., Slater M.J. (2024). Utility of by-products of black soldier fly larvae (*Hermetia illucens*) production as feed ingredients for Pacific whiteleg shrimp (*Litopenaeus vannamei*). *J. World Aquac. Soc.*, 55: e13070.
- Fujaya Y., Trijuno D.D., Aslamyah S., Alam N. (2016). Domestication and selective breeding for producing fast growing and high meat quality of blue swimming crab (*Portunus pelagicus*). *Aquac. Aquarium Conserv. Legis.*, 9: 670–679.
- Gatlin III D.M., Carvalho P.L.P.F.D., Flint C., Miranda C., Tomberlin J.K. (2024). Evaluation of lauric acid enhancement of black soldier fly larvae from coconut. *J. Econ. Entomol.*, 117: 1235–1241.
- Ge C., Cheng H., Li J., Wang H., Ma S., Qin Y., Xue M. (2022). Effects of defatted yellow mealworm (*Tenebrio molitor*) on the feed qualities and the growth performance of largemouth bass (*Micropterus salmoides*). *J. Insects Food Feed.*, 8: 1265–1280.
- Goncalves R., Pfalzgraff T., Lund I. (2024). Impact of live feed substitution with formulated diets on the development, digestive capacity, biochemical composition, and rearing water quality of European lobster (*Homarus gammarus*, L.) larvae. *Aquaculture*, 586: 740776.

- Hahn T., Roth A., Febel E., Fijalkowska M., Schmitt E., Arsiwalla T., Zibek S. (2018). New methods for high-accuracy insect chitin measurement. *J. Sci. Food Agric.*, 98: 5069–5073.
- Han G.M., Zhang J.H., Wu L.M., Kou X.M., Ye X.M., Qin B.L., Bi J.H., Wang S.H., Xu R., Ma L.J., Zhang C.X. (2023). Effects of replacing fish meal with black soldier fly larvae meal on growth, body composition and immunity of red swamp crayfish (*Procambarus clarkii*). *Chin. J. Anim. Nutr.*, 35: 4495–4506.
- Harun H.C., Amiruddin W.M., Leng O.S., Malik S.A., Yee L.S., Rusli N.D., Mat K.B., Mohd M., Sukri S.A.M., Al-Amsyar S.M. (2021). Optimisation of treated black soldier fly larvae (BSFL) using acidic salt to improve protein digestibility of giant freshwater prawn (*Macrobrachium rosenbergii*) larvae. In *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, pp. 012067.
- He Y., Liu X., Zhang N., Wang S., Wang A., Zuo R., Jiang Y. (2022 a). Replacement of commercial feed with fresh black soldier fly (*Hermetia illucens*) larvae in Pacific white shrimp (*Litopenaeus vannamei*). *Aquac. Nutr.*, 2022: 9130400.
- He Y., Zhang N., Wang A., Wang S., Che Y., Huang S., Yi Q., Ma Y., Jiang Y. (2022 b). Positive effects of replacing commercial feeds by fresh black soldier fly (*Hermetia illucens*) larvae in the diets of Pacific white shrimp (*Litopenaeus vannamei*): Immune enzyme, water quality, and intestinal microbiota. *Front. Mar. Sci.*, 9: 987363.
- He Y., Peng H., Jin M., Wang J., Li S., Li M., Zhu T., Zhang L., Chen X., Zhou Q. (2024). Application evaluation of black soldier fly (*Hermetia illucens*) larvae oil in shrimp feed: Effects on growth performance, antioxidant capacity and lipid metabolism. *Aquac. Rep.*, 36: 102174.
- Henry M.A., Golomazou E., Asimaki A., Psoufakis P., Fountoulaki E., Mente E., Rumbos C.I., Athanassiou C.G., Karapanagiotidis I.T. (2022). Partial dietary fishmeal replacement with full-fat or defatted superworm (*Zophobas morio*) larvae meals modulates the innate immune system of gilthead seabream, *Sparus aurata*. *Aquac. Rep.*, 27: 101347.
- Herawati V.E., Elfitasari T., Darmanto Y.S., Anggraeni N., Windarto S. (2023). Effect of different ratios of maggot meal (*Hermetia illucens*) on growth performance and body composition of vannamei shrimp (*Litopennaeus vannamei*) post larvae. *Aquac. Aquar. Conserv. Legis.*, 16: 768–779.
- Herawati W.E., Windarto S., Anggraeni N., Arfan M. (2024). Optimal dietary maggot oil for juvenile white shrimp (*Litopenaeus vannamei*): Growth performance, feed utilization, and nutritional quality. *Aquac. Aquar. Conserv. Legis.*, 17: 61–71.
- Hinchcliffe J., Agnalt A.L., Daniels C.L., Drengstig A.R., Lund I., McMinn J., Powell A. (2022). European lobster *Homarus gammarus* aquaculture: Technical developments, opportunities and requirements. *Rev. Aquac.*, 14: 919–937.
- Hu J.H., Xia W.G., Qing H.W., Xia Z.H., Yan M.W., Hua H.Y. (2019). Effects of fish meal replacement by black soldier fly (*Hermetia illucens*) larvae meal on growth performance, body composition, serum biochemical indexes and antioxidant ability of juvenile *Litopenaeus vannamei*. *Chin. J. Anim. Nutr.*, 31: 5292–5300.
- Hu S., Wang J., Han T., Li X., Jiang Y., Wang C. (2017). Effects of dietary DHA/EPA ratios on growth performance, survival and fatty acid composition of juvenile swimming crab (*Portunus trituberculatus*). *Aquac. Res.*, 48: 1291–1301.
- Hui Y.G., Hong C.Y., Niu Y.Z., Ping C. (2009). Research progress on the larvae and prepupae of black soldier fly *Hermetia illucens* used as animal feedstuff. *Chin. Bull. Entomol.*, 46: 41–45.
- Huseynli L., Parviainen T., Kyllönen T., Aisala H., Vene K. (2023). Exploring the protein content and odor-active compounds of black soldier fly larvae for future food applications. *Future Foods*, 7: 100224.

- Iber B.T., Kasan N.A., Torsabo D., Omuwa J.W. (2022). A review of various sources of chitin and chitosan in nature. *J. Renew. Mater.*, 10: 1097.
- Jiang X., Pan K., Yang Y., Shu-Chien A.C., Wu X. (2022). Dietary DHA oil supplementation promotes ovarian development and astaxanthin deposition during the ovarian maturation of Chinese mitten crab *Eriocheir sinensis*. *Aquac. Nutr.*, 2022: 9997317.
- Jolly C.M., Nyandat B., Yang Z., Ridler N., Matias F., Zhang Z., Murekezi P., Menezes A. (2023). Dynamics of aquaculture governance. *J. World Aquac. Soc.*, 54: 427–481.
- Karthick Rajan D., Mohan K., Rajarajeswaran J., Divya D., Kumar R., Kandasamy S., Zhang S., Ramu Ganesan A. (2024). B-chitin and chitosan from waste shells of edible mollusks as a functional ingredient. *Food Front.*, 5: 46–72.
- Kearney J. (2010). Food consumption trends and drivers. *Phil. Trans. R. Soc. B.*, 365: 2793–2807.
- Keetanon A., Chuchird N., Phansawat P., Kitsanayanyong L., Chou C.C., Verstraete P., Ménard R., Richards C.S., Ducharme F., Rairat T. (2024). Effects of black soldier fly larval meal on the growth performance, survival, immune responses, and resistance to *Vibrio parahaemolyticus* infection of Pacific white shrimp (*Litopenaeus vannamei*). *Aquac. Int.*, 32: 2233–2248.
- Khan J.A., Guo X., Pichner R., Aganovic K., Heinz V., Hollah C., Miert S.V., Verheyen G.R., Juadjur A., Rehman K.U. (2025). Evaluation of nutritional and techno-functional aspects of black soldier fly high-protein extracts in different developmental stages. *Animal*, 19: 101463.
- Ko D., Lee Y., Kim S., Song S., Kim W., Hur S.W., Kim K.W., Lee K.J. (2025). Full-fat or defatted black soldier fly (*Hermetia illucens*) larvae meal as a fish meal replacer in diet for *Penaes vannamei*. *J. Insects Food Feed.*, 1: 1–17.
- Koca S.B., Koca H.U., Özdoğan H.B.E., Yigit N.Ö. (2024). Growth performance and survival rate of *Pontastacus leptodactylus* juveniles fed with fresh black soldier fly *Hermetia illucens* and mealworm *Tenebrio molitor* larvae. *Acta Aquat. Turc.*, 20: 343–350.
- Kouřimská L., Adámková A. (2016). Nutritional and sensory quality of edible insects. *NFS J.*, 4: 22–26.
- Lähteenmäki-Uutela A., Marimuthu S.B., Meijer N. (2021). Regulations on insects as food and feed: a global comparison. *J. Insects Food Feed*, 7: 849–856.
- Lee K.S., Lee M.G., Jeong K., Yun E.Y., Goo T.W. (2025). Medium-chain fatty acids extracted from black soldier fly (*Hermetia illucens*) larvae prevents high-fat diet-induced obesity in vivo in C57BL/6J mice. *Animals*, 15: 1384.
- Li X., Chen Y., Zheng C., Chi S., Zhang S., Tan B., Xie S. (2022). Evaluation of six novel protein sources on apparent digestibility in Pacific white shrimp, *Litopenaeus vannamei*. *Aquac. Nutr.*, 2022: 8225273.
- Liu C.M., Uehara T., Shimoda M. (2024). Enhancing the nutritional value of black soldier fly larvae through the nutrient amino acid transporter suppression in the excretion system. *J. Insects Food Feed.*, 11: 497–507.
- Lu S., Taethaisong N., Meethip W., Surakhunthod J., Sinpru B., Sroichak T., Archa P., Thongpea S., Paengkoum S., Purba R.A.P., Paengkoum P. (2022). Nutritional composition of black soldier fly larvae (*Hermetia illucens* L.) and its potential uses as alternative protein sources in animal diets: A review. *Insects*, 13: 831.
- Maddaloni M., Vassalini I., Alessandri I. (2020). Green routes for the development of chitin/chitosan sustainable hydrogels. *Sustain. Chem.*, 1: 325–344.
- Marono S., Piccolo G., Loponte R., Di Meo C., Attia Y.A., Nizza A., Bovera F. (2015). In vitro crude protein digestibility of *Tenebrio molitor* and *Hermetia illucens* insect meals and its correlation with chemical composition traits. *Ital. J. Anim. Sci.*, 14: 3889.

- McCallum M.L., Weston S.D., Tilahun Y. (2020). Performance of early juvenile giant river prawns (*Macrobrachium rosenbergii*) fed fish, soybean, shrimp and four insect based diets while under low temperature stress. *Proceedings of the Oklahoma Academy of Science*, 100: 5–15.
- Ming C., Wang S., Yun B., Xie S.Q., Qian X.Q. (2024). Effect of dietary replacing fish meal with compound protein source on growth performance, feed utilization, and immune performance of *Litopenaeus vannamei*. *Feed Res.*, 47: 49.
- Miron L., Montevicchi G., Bruggeman G., Macavei L.I., Maistrello L., Antonelli A., Thomas M. (2023). Functional properties and essential amino acid composition of proteins extracted from black soldier fly larvae reared on canteen leftovers. *Innov. Food Sci. Emerg. Technol.*, 87: 103407.
- Mohan K., Ravichandran S., Muralisankar T., Uthayakumar V., Chandirasekar R., Rajeevgandhi C., Rajan D.K., Seedeve P. (2019). Extraction and characterization of chitin from sea snail *Conus inscriptus* (Reeve, 1843). *Int. J. Biol. Macromol.*, 126: 555–560.
- Mohan K., Ganesan A.R., Muralisankar T., Jayakumar R., Sathishkumar P., Uthayakumar V., Chandirasekar R., Revathi N. (2020). Recent insights into the extraction, characterization, and bioactivities of chitin and chitosan from insects. *Trends Food Sci. Technol.*, 105: 17–42.
- Mohan K., Muralisankar T., Jayakumar R., Rajeevgandhi C. (2021). A study on structural comparisons of α -chitin extracted from marine crustacean shell waste. *Carbohydr. Polym. Tech. Appl.*, 2: 100037.
- Mohan K., Rajan D.K., Muralisankar T., Ganesan A.R., Sathishkumar P., Revathi N. (2022 a). Use of black soldier fly (*Hermetia illucens* L.) larvae meal in aquafeeds for a sustainable aquaculture industry: A review of past and future needs. *Aquaculture*, 553: 738095.
- Mohan K., Ganesan A.R., Ezhilarasi P.N., Kondamareddy K.K., Rajan D.K., Sathishkumar P., Rajarajeswaran J., Conterno L. (2022 b). Green and eco-friendly approaches for the extraction of chitin and chitosan: A review. *Carbohydr. Polym.*, 287: 119349.
- Mohan K., Rajan D.K., Divya D., Rajarajeswaran J., Zhang S., Sathishkumar P. (2024). New insights into the organic waste-derived black soldier fly chitin and chitosan for biomedical and industrial applications. *J. Environ. Chem. Eng.*, 12: 114660.
- Mohd-Noor S.N., Wong C.Y., Lim J.W., Mah-Hussin M.I.A., Uemura Y., Lam M.K., Ramli A., Bashir M.J., Tham L. (2017). Optimization of self-fermented period of waste coconut endosperm destined to feed black soldier fly larvae in enhancing the lipid and protein yields. *Renew. Energy*, 111: 646–654.
- Moula N., Scippo M.L., Douny C., Degand G., Dawans E., Cabaraux J.F., Hornick J.L., Medigo R.C., Leroy P., Francis F., Detilleux J. (2018). Performances of local poultry breed fed black soldier fly larvae reared on horse manure. *Anim. Nutr.*, 4: 73–78.
- Munro J., Owens L. (2007). Yellow head-like viruses affecting the penaeid aquaculture industry: a review. *Aquac. Res.*, 38: 893–908.
- Muralisankar T., Mohan K., Udhayakumar V., Balamuralikrishnan B. (2022). Potential role of dietary minerals in fish and crustaceans. In: *Aquaculture Science and Engineering*. Singapore: Springer Nature Singapore, pp. 431–461.
- Novriadi R., Davies S., Triatmaja K.I.K., Hermawan M., Kontara E.K.M., Tanaka B., Rinaldy A., Nugroho J.E. (2023). Black soldier fly (*Hermetia illucens*) as an alternative to marine ingredients elicits superior growth performance and resistance to *Vibrio harveyi* infection for pacific white shrimp (*Litopenaeus vannamei*). *Turk. J. Fish. Aquat. Sci.*, 24: TRJFAS24343.
- Nunes A.J., Yamamoto H., Simões J.P., Pisa J.L., Miyamoto N., Leite J.S. (2023). The black soldier fly (*Hermetia illucens*) larvae meal can cost-effectively replace fish meal in

- practical nursery diets for post-larval *Penaeus vannamei* under high-density culture. *Fishes*, 8: 605.
- Oh J., Kim H., Park K., Kim B.G. (2024). Drying methods for black soldier fly (*Hermetia illucens*) larvae as a feed ingredient for pigs affect in vitro nutrient disappearance. *Agriculture*, 14: 1792.
- Olsen R.L., Hasan M.R. (2012). A limited supply of fishmeal: Impact on future increases in global aquaculture production. *Trends Food Sci. Technol.*, 27: 120–128.
- Özdoğan H.B.E., Bahadır Koca S., Özmen Ö., Erol K.G., Özkök R., Uzunmehmetoğlu O.Y., Öztuna İ.H., Koca H.U., Yiğit N.Ö. (2024). The on growth, histology of intestinal and hepatopancreas of using black soldier fly (*Hermetia illucens*) larvae meal in the diets of *Pontastacus leptodactylus* juvenile. *J. Appl. Aquac.*, 37: 308–320.
- Pascon G., Opere Akinyi R., Cardinaletti G., Daniso E., Messina M. (2025). Chitin and its effects when included in aquafeed. *Aquac. Int.*, 33: 202–224.
- Qiao F., Zhang R., Shi Y., Qiu Z., Wu X., Wang X., Zhang L. (2025). Dietary supplementation with black soldier fly slurry regulates physiological metabolism to improve ovarian odour quality of adult *Eriocheir sinensis*. *J. Insects Food Feed.*, 1: 1–17.
- Raja Hishamudin R.M.H. (2020). Black soldier fly *Hermetia illucens* larvae as protein source for giant freshwater prawn *Macrobrachium rosenbergii* larvae feed (Doctoral dissertation, Universiti Malaysia Kelantan). <http://discol.umk.edu.my/id/eprint/4331>
- Rajan P.R., Ramasamy P., Purushothaman V., Brennan G.P. (2000). White spot baculovirus syndrome in the Indian shrimp *Penaeus monodon* and *P. indicus*. *Aquaculture*, 184: 31–44.
- Rampure S.M., Velayudhannair K., Marimuthu N. (2023). Characteristics of chitin extracted from different growth phases of black soldier fly, *Hermetia illucens*, fed with different organic wastes. *Int. J. Trop. Insect Sci.*, 43: 979–987.
- Rangel F., Monteiro M., Santos R.A., Ferreira-Martins D., Cortinhas R., Gasco L., Gai F., Pousão-Ferreira P., Couto A., Oliva-Teles A., Serra C.R. (2024). Novel chitinolytic *Bacillus* spp. increase feed efficiency, feed digestibility, and survivability to *Vibrio anguillarum* in European seabass fed with diets containing *Hermetia illucens* larvae meal. *Aquaculture*, 579: 740258.
- Rasdi F.L.M., Ishak A.R., Hua P.W., Shaifuddin S.N.M., Dom N.C., Kari Z.A., Yatim S.R.M., Edinur H.A., Mokhtar M.A.M., Rashid R.I.M. (2023). Evaluating the growth and development of black soldier fly (BSF) (*Hermetia Illucens* (L.)) (Diptera: Stratiomyidae) larvae reared on different agricultural waste materials. *Serangga*, 28: 55–68.
- Rehman K.U., Hollah C., Wiesotzki K., Rehman R.U., Rehman A.U., Zhang J., Zheng L., Nienaber T., Heinz V., Aganovic K. (2023). Black soldier fly, *Hermetia illucens* as a potential innovative and environmentally friendly tool for organic waste management: A mini-review. *Waste Manag. Res.*, 41: 81–97.
- Ribeiro N., Costa R., Ameixa O.M. (2022). The influence of non-optimal rearing conditions and substrates on the performance of the black soldier fly (*Hermetia illucens*). *Insects*, 13: 639.
- Richardson A., Dantas-Lima J., Lefranc M., Walraven M. (2021). Effect of a black soldier fly ingredient on the growth performance and disease resistance of juvenile Pacific white shrimp (*Litopenaeus vannamei*). *Animals*, 11: 1450.
- Romano N., Sinha A., Powell A., Fischer H. (2023). Mineral composition in black soldier fly (*Hermetia illucens*) larvae and resulting frass from fruit and their peels. *J. Insects Food Feed.*, 9: 43–54.
- Saputra I., Fotedar R. (2023). The effect of defatted black soldier fly (*Hermentia illucens*) meal inclusion in the formulated feed on the pellet stability at different salinity levels. *Proc. MATEC Web of Conferences*, EDP Sciences, pp. 01014.

- Saputra I., Fotedar R. (2024). The effect of defatted black soldier fly meal (*Hermetia illucens*) inclusion in the formulated diet on the growth, gene expression, and histopathology of juvenile lobster (*Panulirus ornatus* Fabricius, 1798). *Aquac Int.*, 32: 11–29.
- Saputra I., Lee Y.N., Fotedar R. (2024). The effect of supplementation of fish protein hydrolysate to the BSF-based aquafeed on the growth, survival, fatty acids, and histopathology of juvenile lobster (*Panulirus ornatus*). *Aquac. Nutr.*, 2024: 8579991.
- Shin J., Jo S., Ko D., Lee K.J. (2020). Replacing fish meal with black soldier fly larvae and mealworm larvae in diets for Pacific white shrimp *Litopenaeus vannamei*. *Korean J. Fish. Aquat. Sci.*, 53: 900–908.
- Shin J., Shin J., Eom G., Lee K.J. (2021). Effects of dietary mealworm *Tenebrio molitor* larvae and black soldier fly *Hermetia illucens* larvae on pacific white shrimp *Litopenaeus vannamei*: Innate immune responses, anti-oxidant enzyme activity, disease resistance against *Vibrio parahaemolyticus* and growth. *Korean J. Fish. Aquat. Sci.*, 54: 624–633.
- Shin J., Hasanthi M., Lee K.J. (2025). Replacing fish oil with black soldier fly (*Hermetia illucens*) larvae oil in diets for *Penaeus vannamei*: Effects on growth and fatty acid composition. *J. Insects Food Feed.*, 1: 1–20.
- Siddiqui S.A., Ristow B., Rahayu T., Putra N.S., Yuwono N.W., Mategeko B., Smetana S., Saki M., Nawaz A., Nagdalian A. (2022). Black soldier fly larvae (BSFL) and their affinity for organic waste processing. *Waste Manag.*, 140: 1–13.
- Srisuksai K., Limudomporn P., Kovitvadhi U., Thongsuwan K., Imaram W., Lertchaiyongphanit R., Sareepoch T., Kovitvadhi A., Fungfuang W. (2024). Physicochemical properties and fatty acid profile of oil extracted from black soldier fly larvae (*Hermetia illucens*). *Vet. World.*, 17: 518.
- Stamer A. (2015). Insect proteins – a new source for animal feed: The use of insect larvae to recycle food waste in high-quality protein for livestock and aquaculture feeds is held back largely owing to regulatory hurdles. *EMBO Rep.*, 16: 676–680.
- Stentiford G.D., Neil D.M., Peeler E.J., Shields J.D., Small H.J., Flegel T.W., Vlcek J.M., Jones B., Morado F., Moss S., Lotz J. (2012). Disease will limit future food supply from the global crustacean fishery and aquaculture sectors. *J. Invertebr. Pathol.*, 110: 141–157.
- Subchan W., Nawangsari F.D., Prihatin J. (2024). The effect of flour-based feed black soldier fly larvae on crayfish (*Cherax quadricarinatus* von Martens) growth. *Proc. BIO Web of Conferences*, EDP Sciences, pp. 01005.
- Syafaat M.N., Azra M.N., Waiho K., Fazhan H., Abol-Munafi A.B., Ishak S.D., Syahnnon M., Ghazali A., Ma H., Ikhwanuddin M. (2021). A review of the nursery culture of mud crabs, genus *Scylla*: current progress and future directions. *Animals*, 11: 2034.
- Tariq M.R., Liu S., Wang F., Wang H., Mo Q., Zhuang Z., Zheng C., Liang Y., Liu Y., Ur Rehman K., Helvacı M. (2025). Black soldier fly: A keystone species for the future of sustainable waste management and nutritional resource development: A review. *Insects*, 16: 750.
- Terrey D., James J., Tankovski I., Dalim M., van Spankeren M., Chakraborty A., Schmitt E., Paul A. (2021). Palatability enhancement potential of *Hermetia illucens* larvae protein hydrolysate in *Litopenaeus vannamei* diets. *Molecules*, 26: 1582.
- Truong H.H., Moss A.F., Bourne N.A., Simon C.J. (2020). Determining the importance of macro and trace dietary minerals on growth and nutrient retention in juvenile *Penaeus monodon*. *Animals*, 10: 2086.
- Truong H.H., Hines B.M., Emerenciano M.G., Blyth D., Berry S., Noble T.H., Bourne N.A., Wade N., Rombenso A.N., Simon C.J. (2023). Mineral nutrition in penaeid shrimp. *Rev. Aquac.*, 15: 1355–1373.
- Udomsil N., Imsoonthornruksa S., Gosalawit C., Ketudat-Cairns M. (2019). Nutritional values and functional properties of house cricket (*Acheta domesticus*) and field cricket (*Gryllus*

- bimaculatus*). Food Sci. Technol. Res., 25: 597–605.
- Villarreal H. (2023). Shrimp farming advances, challenges, and opportunities. J. World Aquac. Soc., 54: 1092.
- Wang G., Peng K., Hu J., Mo W., Wei Z., Huang Y. (2021). Evaluation of defatted *Hermetia illucens* larvae meal for *Litopenaeus vannamei*: effects on growth performance, nutrition retention, antioxidant and immune response, digestive enzyme activity and hepatic morphology. Aquac. Nutr., 27: 986–997.
- Wang H., ur Rehman K., Feng W., Yang D., ur Rehman R., Cai M., Zhang J., Yu Z., Zheng L. (2020). Physicochemical structure of chitin in the developing stages of black soldier fly. Int. J. Biol. Macromol., 149: 901–907.
- Wang H., Li E., Huang Q., Liu J., Miao Y., Wang X., Qin C., Qin J., Chen L. (2024). Growth and hepatopancreas health of juvenile chinese mitten crab (*Eriocheir sinensis*) fed different levels of black soldier fly (*Hermetia illucens*) larvae meal for fish meal replacement. Aquac. Nutr., 2024: 6625061.
- Wang T., Wang X., Shehata A.I., Wang R., Yang H., Wang Y., Wang J., Zhang Z. (2022). Growth performance, physiological and antioxidant capacity responses to dietary fish meal replacement with insect meals for aquaculture: A case study in red claw crayfish (*Cherax quadricarinatus*). Aquac. Res., 53: 3853–3864.
- Wu N., Wang X., Xu X., Cai R., Xie S. (2020). Effects of heavy metals on the bioaccumulation, excretion and gut microbiome of black soldier fly larvae (*Hermetia illucens*). Ecotoxicol. Environ. Saf., 192: 110323.
- Yandi I., Öztürk R.Ç., Kocabas M., Kurtoglu I.Z., Altinok I. (2023). Nutritional composition of black soldier fly (*Hermetia illucens*) reared on chicken waste meal, fruit and vegetable waste, and their mixture. J. Insects Food Feed., 9: 557–568.
- Yang Q., Fan R., Ma Z., Jiang S., Huang J., Yang L., Li Y., Yang R., Hu J., Zhou S., Su Q. (2023). Effects of replacing dietary fishmeal with zymolytic black soldier fly larvae on the growth performance of the mud crab (*Scylla paramamosain*) larvae. Isr. J. Aquac. – Bamidgeh., 75. doi:10.46989/001c.89728.
- Yao W., Zhang C., Mao H., Hua G., Liu Q., Zhao S., Shuang H., Poolsawat L., Yuan S., Wang J., Wang Q. (2024). Effects of dietary defatted black soldier fly (*Hermetia illucens*) larvae meal substituting fish meal on growth, antioxidative capacity, immunity, intestinal histology and microbiota of juvenile Chinese mitten crab (*Eriocheir sinensis*). Aquac. Rep., 38: 102302.
- Yildirim-Aksoy M., Eljack R., Beck B.H., Peatman E. (2022). Nutritional evaluation of frass from black soldier fly larvae as potential feed ingredient for Pacific white shrimp, *Litopenaeus vannamei*. Aquac. Rep., 27: 101353.
- Zainol Abidin N.A., Kormin F., Zainol Abidin N.A., Mohamed Anuar N.A.F., Abu Bakar M.F. (2020). The potential of insects as alternative sources of chitin: An overview on the chemical method of extraction from various sources. Int. J. Mol. Sci., 21: 4978.
- Zamani A., Jafari M. (2025). Effects of fish meal replacement with black soldier fly larvae meal in the diet of Pacific white shrimp, *Litopenaeus vannamei* post-larvae on growth performance and digestive enzymes activity. Aquac. Anim. Nutr., 10: 19.
- Zarantoniello M., Chemello G., Ratti S., Pulido-Rodríguez L.F., Daniso E., Freddi L., Salinetti P., Nartea A., Bruni L., Parisi G., Riolo P. (2023). Growth and welfare status of giant freshwater prawn (*Macrobrachium rosenbergii*) post-larvae reared in aquaponic systems and fed diets including enriched black soldier fly (*Hermetia illucens*) prepupae meal. Animals, 13: 715.
- Zhang W.R., Liu H.X., Wang Z., Wang X.J., Wu Y.B., Qian Z.C., Wang J. (2023). Effect of defatted black soldier fly larvae meal on nutritional quality of *Scylla paramamosain*. Feed Res., 46: 51.

- Zhang Z.L., Meng Y.Q., Li J.J., Zhang X.X., Li J.T., Xu J.R., Zheng P.H., Xian J.A., Lu Y.P. (2024). Effects of antimicrobial peptides from dietary *Hermetia illucens* larvae on the growth, immunity, gene expression, intestinal microbiota and resistance to *Aeromonas hydrophila* of juvenile red claw crayfish (*Cherax quadricarinatus*). *Fish Shellfish Immunol.*, 147: 109437.
- Zheng J.Y., Gan Z.R., Huang T.Y., Xiao Y., Xu W.Y., Li X.Q., Leng X.J. (2024). Replacement of fish meal with defatted black soldier fly (*Hermetia illucens*) in diet of Pacific white shrimp (*Litopenaeus vannamei*): growth, flesh quality and transcriptome. *J. Insects Food Feed.*, 1: 1–21.
- Zheng L., Hou Y., Li W., Yang S., Li Q., Yu Z. (2012). Biodiesel production from rice straw and restaurant waste employing black soldier fly assisted by microbes. *Energy*, 47: 225–229.
- Zulkifli N.F.N.M., Seok-Kian A.Y., Seng L.L., Mustafa S., Kim Y.S., Shapawi R. (2022). Nutritional value of black soldier fly (*Hermetia illucens*) larvae processed by different methods. *PloS One*, 17: e0263924.

Received: 24 VIII 2025

Accepted: 30 X 2025

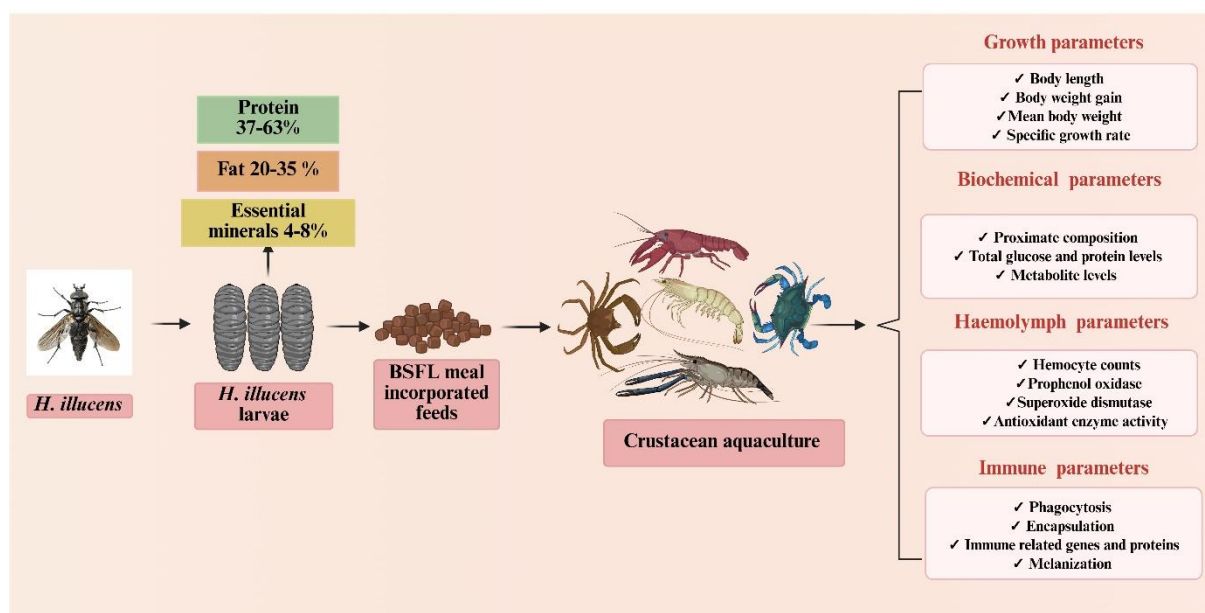


Figure 1. Overall illustration of black soldier fly larvae meal in crustacean aquaculture

Table 1. Black soldier fly (*Hermetia illucens*) larvae meal as potential feed ingredient for crustacean aquaculture

S.No	Inclusion level	Level of replacement	Duration of the study (days)	Growth performance	Survival rate	Body biochemical parameters	Immune response	Blood parameters	Digestibility/Nutrient utilization	References
Pacific white shrimp (<i>Litopenaeus vannamei</i>)										
1	0, 5, 10, 20 and 30%	50%	84	↑ Weight gain (5%)	n.d.	↑ Fillet lipid content (20%)	Inhibition of <i>Vibrio parahaemolyticus</i> (20%)	No significant change in THC, hemocyanin, serum protein, cholesterol	n.d.	Yildirim-Aksoy et al., 2022
2	0, 10, 20 and 30%	10–20%	49	↓ Growth rate (30%)	n.d.	↓ Lipid content; ↑ CPT, SOD, IDH activities	↑ Antioxidant enzymes	↓ ACP, ALP, lipase (30%)	n.d.	Chen et al., 2023 a
3	0, 1, 1.5, and 2%	n.d.	42	↑ Growth, feed and protein efficiency	No significant effect	↑ Protein retention	n.d.	n.d.	n.d.	Herawati et al., 2024
4	0, 25, 50, 75 and 100%	34.92%	56	↑ % weight gain (75%)	n.d.	↑ Lauric acid; lipid-related gene expression	↑ Immune-related gene expression	↑ ACP, PO, NOS	n.d.	He et al., 2024
5	n.d.	n.d.	28	↓ Growth	No significant effect	n.d.	n.d.	n.d.	↓ Digestibility of protein and dry matter	Li et al., 2022
6	0, 25, 50, 75 and 100%	50%	45	↑ Weight gain (25%)	↑ Survival (25%)	↑ Hepatosomatic index	↑ SOD, GPx	n.d.	↑ Protease activity (25%)	He et al., 2022 a
7	n.d.	24%	n.d.	↑ RGR, FCR, protein efficiency	n.d.	↑ Amino acid and fatty acid profile	n.d.	n.d.	n.d.	Herawati et al., 2023
8	0, 7, 14, 21, 28 and 36%	36%	63	↓ Weight gain and SGR	n.d.	↓ Whole-body protein and lipid	n.d.	n.d.	n.d.	Cummins et al., 2017
9	n.d.	n.d.	45	n.d.	↑ Survival	n.d.	↑ PO, SOD, immune gene expression	n.d.	n.d.	Shin et al., 2021
10	0, 25, 50, 75 and 100%	50%	45	n.d.	n.d.	↑ Hepatosomatic index	↑ SOD, GPx	n.d.	↑ Protease activity (25%)	He et al., 2022 b
11	0, 25, 50, 75 and 100%	26.46%	n.d.	↑ Growth performance	n.d.	n.d.	n.d.	n.d.	↑ FCR	Nunes et al., 2023
12	0, 10, 20, and 30%	75%	49	n.d.	↑ Survival (10%)	↓ Intestinal folds (20–30%)	↑ AMP genes	n.d.	n.d.	Chen et al., 2021
13	0, 25, 50, 75 and 100%	50%	45	n.d.	n.d.	n.d.	↑ Gut microbiota diversity	n.d.	n.d.	He et al., 2024
14	Exuviae, cocoons, imago	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	↑ Protein digestibility	Fricke et al., 2024
15	Multi-insect meals	n.d.	65	↑ Growth (BSF best)	n.d.	↑ AA and FA content	↑ Antioxidant enzymes	n.d.	↑ ADC	Shin et al., 2021
16	0, 1 and 2%	n.d.	n.d.	↑ Palatability	n.d.	↑ Free AA content	n.d.	n.d.	n.d.	Terrey et al., 2021

17	0, 20, 40, 60, 80 and 100%	20%	60	↓ Flesh protein, collagen	n.d	↑ PUFA, free AA	n.d.	n.d.	n.d.	Zheng et al., 2024
18	0, 0.5 to 5%	50%	90	↑ Growth and feed efficiency	↑ Against <i>V. harveyi</i>	n.d.	↑ THC, lysozyme	n.d.	n.d.	Novriadi et al., 2023
19	0, 20, 40, and 60%	n.d.	57	↑ Growth (40–60%)	n.d.	n.d.	↑ PO, SOD, GPx	n.d.	n.d.	Shin et al., 2020
20	0, 10, 20, 30, 40 and 50%	n.d.	60	↓ Growth	n.d.	n.d.	↑ TRAF6, TOLL1 genes	n.d.	n.d.	Chen et al., 2023 b
21	0, 7.5, 15 and 22.5%	22.5%	49	No sig. change	n.d.	↑ Protein content	n.d.	n.d.	n.d.	Fahrur et al., 2021
22	0, 15, 30, 45, 60 and 80%	60%	56	↓ Growth (80%)	n.d.	↓ Crude protein	↑ TAC (80%)	n.d.	n.d.	Wang et al., 2021
23	0, 10, 15, 20, 25 and 30%	30%	56	↑ Growth and SGR (10–30%)	n.d.	↑ Calcium (25%)	↑ TAC, POD, CAT (20%)	n.d.	n.d.	Hu et al., 2019
24	0, 20, 40, 60, 80 and 100%	80%	56	↑ Growth (80%)	↑ Survival (100%)	↑ AST, ALT, cholesterol (100%)	↓ GPx, SOD (100%)	n.d.	n.d.	Ming et al., 2024
25	0, 10, 20 and 30%	n.d.	49	↓ Growth (30%)	No significant difference	↓ Lipid, TAG, cholesterol	Gene regulation changes	n.d.	n.d.	Chen et al., 2022
26	0, 2, 5 and 10%	5–10%	45	↑ Weight gain	↑ Survival	↓ <i>Vibrio</i> spp. count	↑ Immune parameters	n.d.	n.d.	Keetanon et al., 2024
27	0, 4.12, 8.24, 12.36, 16.48 and 20.61%	75%	56	No significant effect (≤20.61%)	n.d.	↓ Inflammation (>16.48%)	↑ Antioxidant capacity	n.d.	n.d.	Chang et al., 2025
28	n.d.	n.d.	83	↑ Weight gain	n.d.	↓ Protein digestibility	–	n.d.	n.d.	Candela-Maldonado et al., 2025
29	0, 5, 10 and 15%	n.d.	56	↑ Growth	n.d.	↑ Lauric acid	↑ PO, LZM, GPx, immune genes	n.d.	n.d.	Ko et al., 2025
30	0, 25, 50, 75 and 100%	n.d.	56	↑ Growth (100%)	↑ Survival	↑ Fatty acid content	↑ SOD, GPx	n.d.	n.d.	Shin et al., 2025
31	0, 25, 50 and 100%	n.d.	70	↑ Growth (50%)	n.d.	n.d.	n.d.	n.d.	↑ Trypsin and lipase (50%)	Zamani and Jafari, 2025
Freshwater shrimp (<i>Macrobrachium rosenbergii</i>)										
32	n.d.	n.d.	7	↑ Growth	n.d.	n.d.	n.d.	n.d.	n.d.	McCallum et al., 2020
33	0, 3 and 20%	n.d.	60	No negative effect	No significant effect	↑ α -tocopherol, carotenoids	No significant change in immune genes	↑ B cells	n.d.	Zarantoniello et al., 2023

34	0, 15, 30 and 45%	n.d.	35	↑ Growth	↑ Survival	n.d.	n.d.	n.d.	n.d.	Raja Hishamudin, 2020
35	0, 5, 10 and 15%	50%	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	↑ Protein digestibility	Harun et al., 2021
36	0, 5, 10 and 15%	n.d.	n.d.	n.d.	n.d.	↑ Protein, lipid	n.d.	n.d.	↑ Protein digestibility	Amiruddin et al., 2021
Freshwater crayfish										
37	0 and 12%	n.d.	56	↑ Growth	n.d.	n.d.	↑ Immune gene expression	↑ THC	↑ <i>Lactobacillus</i> in gut	Foysal et al., 2021
38	n.d.	n.d.	60	n.d.	n.d.	↑ Protein, energy in muscle	↑ Immune enzymes	↑ THC	↑ Bacterial activity	Foysal et al., 2019
39	n.d.	n.d.	60	↑ Growth	↑ Survival	n.d.	n.d.	n.d.	n.d.	Koca et al., 2024
40	0, 50 and 100%	n.d.	98 days	↑ Growth	↑ Survival	↑ FA (C16:0, C18:1, C18:2)	n.d.	n.d.	n.d.	Alvanou et al., 2023
41	0, 20, 40, 60, 80, and 100%	40%	60 days	↑ Growth	–	–	n.d.	n.d.	n.d.	Özdoğan et al., 2024
42	n.d.	n.d.	56 days	↑ Growth	n.d.	↑ FA, EPA, DHA	↑ SOD, PO, GPx	n.d.	↑ Digestibility	Chu and Huang, 2024
43	0, 50, 100, 150 and 200 mg/kg AMP	n.d.	56 days	↑ Growth (100–150 mg/kg)	↑ Resistance to <i>A. hydrophila</i>	n.d.	↑ Immune enzymes and gene expression	n.d.	↑ Gut microbiota	Zhang et al., 2024
44	0, 7, 14, 21 and 28%	17.1%	60 days	↑ Growth (14%)	n.d.	↓ MDA (14%)	↑ SOD, GPx, CAT	n.d.	n.d.	Wang et al., 2022
45	n.d.	n.d.	28 days	No sig. growth	n.d.	n.d.	n.d.	n.d.	↓ FCR	Subchan et al., 2024
46	0, 20, 40, 60, 80 and 100%	34.25%	90 days	↑ Growth (40%)	n.d.	↑ Protein (80%)	↑ Lysozyme, SOD	n.d.	↑ Nutrient efficiency	Han et al., 2023
Crab										
47	0, 25, 50, 75 and 100%	50%	56 days	↑ Growth (25–50%)	↑ Survival (25–50%)	n.d.	↑ ACP, ALP, LZM	n.d.	↑ Intestinal folds	Yao et al., 2024
48	0, 6, 12, 18 and 24%	n.d.	n.d.	n.d.	n.d.	↑ Ovarian lipid metabolism	n.d.	n.d.	n.d.	Qiao et al., 2025
49	0, 10, 20, 30, 40 and 50%	50%	56 days	↓ Growth (50%)	n.d.	n.d.	↓ Antioxidant enzymes	n.d.	n.d.	Wang et al., 2024
50	0, 5, 10 and 15%	10%	56 days	↑ Growth (10%)	n.d.	↑ Protein, lipid	↑ Digestive enzyme activity	n.d.	n.d.	Yang et al., 2023
51	0, 25, 50 and 75%	25–50%	28 days	↑ Growth (25–50%)	n.d.	↓ PUFA (75%)	n.d.	n.d.	n.d.	Zhang et al., 2023
Lobster										
52	n.d.	15%	n.d.	n.d.	n.d.	↑ Body glycogen	n.d.	n.d.	↑ Chitinase activity	Goncalves et al., 2024
53	25%	n.d.	56 days	↑ Growth	n.d.	↑ MUFA, SFA, ω9 FA	n.d.	n.d.	n.d.	Saputra et al., 2024

54	0, 25, 35 and 50%	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	↓ Feed dry matter loss (high salinity)	Saputra and Fotedar, 2023
55	0, 25, 35 and 50%	50%	56 days	No sig. effect	n.d.	n.d.	↑ Inflammatory cytokines (35%)	n.d.	n.d.	Saputra and Fotedar, 2024

AA: amino acid, ACP: acid phosphatase, ADC: apparent digestibility coefficients, ALP: alkaline phosphatase, ALT: alanine aminotransferase, AMP: antimicrobial peptides, AST: aspartate aminotransferase, CPT: crude protein, DHA: docosahexaenoic acid, EPA: eicosapentaenoic acid, FA: fatty acid, FCR: feed conversion ratio, GPx: glutathione peroxidase, IDH: isocitrate dehydrogenase, LZM: lysozyme activity, MDA: malondialdehyde activity, MUFA: monounsaturated fatty acids, n.d. – not detected, NOS: nitric oxide synthase, PO: phenoloxidase activity, PUFA: polyunsaturated fatty acids, SFA: saturated fatty acids, SGR: specific growth rate, SOD: superoxide dismutase, TAC: total antioxidant capacity, THC: total hemocyte count, TRAF6: tumor necrosis factor receptor-associated factor 6, ω9 FA: omega-9 polyunsaturated fatty acid.