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Feature Article

Review of Black Soldier Fly (*Hermetia illucens* L.) as a Sustainable Protein Source in Aquaculture: Nutritional Limitations and Improvement Strategies

I-Pei Kuo[1,*], Yi-Jui Hsieh[2], and Shuenn-Der Yang[3]

Abstract

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Fishmeal is the primary protein source in aquaculture feed; however, due to limitations in marine resources, the global supply of fishmeal can no longer meet the rapidly growing demands of the aquaculture industry. Black soldier fly (*Hermetia illucens*) has the ability to efficiently convert inedible organic by-products into protein and is considered a sustainable alternative to fishmeal. However, black soldier fly larvae fed on plant-based substrates often face the nutritional limitations of low protein content and inadequate essential amino acids and fatty acids. These deficiencies may negatively impact fish growth performance, immune response, and flesh quality. Additionally, chitin, a major component of insect exoskeletons, has a controversial role in fish feed. While some studies indicate that chitin positively affects fish health, others have found that it acts as an anti-nutritional factor for certain fish species. This review evaluates the nutritional potential of black soldier fly meal in aquaculture feed. The primary limiting amino acids in black soldier fly meal include arginine, isoleucine, lysine, and methionine, while the major limiting fatty acids are eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). To enhance the nutritional quality of black soldier fly larvae, this review focuses on analyzing their protein content, amino acid and fatty acid profiles, and the effects of chitin. Furthermore, potential improvement strategies, including defatting processes, substrate manipulation, and chitin removal, are discussed.

Key words: Black soldier fly, Aquaculture, Amino acid, Fatty acid, Chitin.

INTRODUCTION

Aquaculture is a fast-growing industry that plays a key role in the food supply. In 2022, global aquaculture production reached 94 million tonnes, surpassing capture fisheries for the first time (FAO 2024). Fishmeal (FM), which contains 60–72% crude protein, has been used as a primary protein source in fish diets (Cho & Kim 2011; Luthada-Raswiswi *et al*. 2021). According to estimates from the Marine Ingredients Organisation, over 87% of FM was used in the aquaculture industry in 2021 (FAO 2024). However, the primary ingredients for FM production are wild-caught fish, such as anchovy (*Engraulis ringens* J.), Jack mackerel (*Trachurus murphyi* N.), sardine (*Strangomera bentincki*), menhaden (*Brevoortia tyrannus*), and Alaska pollock (*Theragra chalcogramma*) (Hall 2010). Due to overfishing, climate

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* Corresponding author, e-mail: ipkuo@mail.ntou.edu.tw
[1] Assistant Professor, Department of Aquaculture, National Taiwan Ocean University, Keelung, Taiwan, ROC.
[2] Associate Research Fellow, Penghu Fisheries Biology Research Center, Fisheries Research Institute, Penghu County, Taiwan, ROC.
[3] Research Fellow, Freshwater Aquaculture Research Center, Fisheries Research Institute, Changhua County, Taiwan, ROC.

change, and ocean pollution, the limited supply of FM is insufficient to meet aquaculture demands (Shahidul Islam & Tanaka 2004; Olsen & Hasan 2012; Jannathulla *et al*. 2019). Therefore, developing alternatives to FM is crucial for ensuring sustainability in aquaculture.

Regarding protein content, environmental sustainability, consumer acceptance, and feasibility, insect meal is one of the most promising alternatives to FM (Hua *et al*. 2019). Among various insects, black soldier fly (BSF; *Hermetia illucens*) has received significant research attention due to its outstanding efficiency and biosecurity. BSF can convert organic waste into insect protein with a superior feed conversion ratio (1.4–2.6), compared to other insects, such as yellow mealworm (*Tenebrio molitor*; 3.8–19.1) and house cricket (*Acheta domesticus*; 2.3–6.1) (Oonincx *et al*. 2015). Secondly, no entomopathogen outbreak has been documented in BSF production up to the present. Their high resistance to disease infection reduces the risk in commercial production (Joosten *et al*. 2020). Thirdly, a feeding trial revealed that the BSF does not exhibit bioaccumulation effects for mycotoxin (Deoxynivalenol, Aflatoxin B1/B2/G2, Ochratoxin A, and Zearalenone) and pesticide (Chlorpyrifos, Chlorpyrifos-methyl, Pirimiphos-methyl). Moreover, the reduced pesticide levels detected in the residual substrate suggested that BSF may have the ability to degrade pesticides (Purschke *et al*. 2017). Further studies have proved that the ability of BSF to degrade Aflatoxin B1 and antibiotics (ciprofloxacin, tylosin, and enrofloxacin) primarily stems from the microorganisms in its gut (Mei *et al*. 2022; Yang *et al*. 2022; Suo *et al*. 2023).

BSF belongs to the phylum Arthropoda, class Insecta, order Diptera, and family Stratiomyidae. The life cycle of BSF is divided into five stages, namely egg, larvae (five instars), prepupae (sixth instar), pupae, and adult. The adults-only consume water and do not have stingers. Therefore, they are regarded as harmless insects to humans and can even be reared in residential areas for organic waste disposal. The larva is the only stage that consumes food and is generally reared for 2–4 wk (Basri *et al*. 2022; Purkayastha & Sarkar 2022). Upon developing into the prepupae stage, they stop feeding and migrate from the substrate. Leveraging this behavior, the technology of self-harvesting can be developed to reduce operational costs (Giannetti *et al*. 2022).

Research on replacing FM with BSF meal has been extensively conducted. However, the optimal FM replacement level varies greatly across different studies. The potential adverse effects of excessive dietary inclusion of BSF on fish include growth retardation, intestinal damage, coloration reduction, nutrition composition decline, and flesh quality impairment (Huang *et al*. 2022; Khieokhajonkhet *et al*. 2022; Kuo *et al*. 2022; Yamamoto *et al*. 2022). In addition to differences between fish species, the nutritional requirements of fish are also determined by various factors, such as growth stage, water quality, feeding regime, and feed processing condition (Jobling 2016). However, the lack of standardization in BSF meal quality may be a greater challenge for feed manufacturing due to their high plasticity in nutritional profile (Barragan-Fonseca *et al*. 2021; Siva Raman *et al*. 2022). Several studies have shown that the proximate composition, fatty acid profile, and amino acid profile can be manipulated by feeding substrates (Liland *et al*. 2017; Fuso *et al*. 2021; Rodrigues *et al*. 2022). In addition, the harvest stage and processing method are also crucial factors that affect the quality of BSF meal (Huang *et al*. 2019; Do *et al*. 2020).

Although BSF meal is regarded as a potential FM alternative and has been commercially produced, its grading standard has not yet been established. Since only a few studies address the quality of BSF from the perspective of aquaculture, this literature review aims to provide an overview of its limited nutritional value and summarize a possible improvement strategy based on fish's nutritional requirements.

NUTRITIONAL VALUE

Proximate composition

The proximate composition and chitin content of BSF fed on various substrates are listed in Table 1. The body composition of BSF is greatly altered by the feeding substrates. The crude protein (conversion factor of 6.25) and lipid content of BSF ranged from 30.8–59.8% and 21.6–40.7%, respectively. The highest protein content was observed in the BSF fed on brewery by-products. Moreover, a correlation matrix between the proximate composition of substrates and the body composition of BSF is illustrated in Fig. 1. The crude protein content of substrates was positively correlated with the crude protein of BSF ($P < 0.05$). However, a negative correlation was found between the crude protein of substrates and the crude lipid of BSF ($P < 0.05$). These results indicate that feeding BSF with low-protein substrates leads to lower protein but higher lipid accumulation.

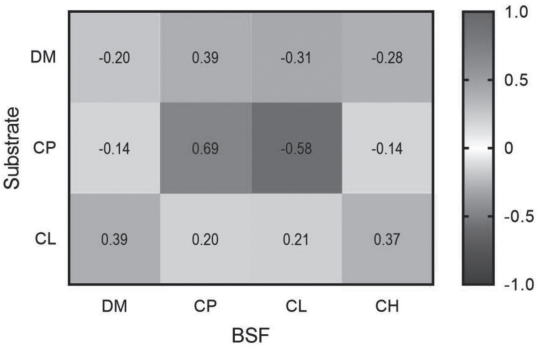


Fig. 1. Correlation matrix between the proximate composition of substrates and the body composition of black soldier fly (BSF). DM: dry matter; CP: crude protein; CL: crude lipid; CH: chitin. Values in the cells represents the Pearson's correlation coefficients.

Table 1. Proximate composition and chitin content of black soldier fly (BSF) fed with various substrates.

	Substrate[z]			BSF				
Feeding substrates	DM	CP	CL	DM	CP	CL	Chitin	Reference
Food waste	17.7	20.2	19.4	41.0	39.5	38.1	8.1	Hosseindoust *et al*. (2023)
Tofu byproduct	24.1	29.2	11.2	42.9	43.5	37.0	8.7	
Vegetable	11.1	13.1	8.6	38.0	37.7	34.5	7.1	
Chicken feed	25.8	17.5	5.3	38.7	41.2	33.6	6.2	Spranghers *et al*. (2017)
Digestate	24.3	24.6	6.2	38.6	42.2	21.8	5.6	
Vegetable waste	12.7	8.6	2.1	41.0	39.9	37.1	5.7	
Restaurant waste	26.2	15.7	13.9	38.1	43.1	38.6	6.7	
Vegetable + fruit waste[y]	8.3	12.0	2.6	22.0	41.9	26.3	6.2	Meneguz *et al*. (2018)
Fruit waste	13.2	4.6	2.8	28.3	30.8	40.7	5.6	
Winery byproduct	35.8	11.7	7.9	26.5	34.4	32.2	5.3	
Brewery byproduct	23.2	20.1	8.7	29.1	53.0	29.9	1.4	
Chicken feed	31.2	19.5	4.5	29.5	43.6	32.9	5.1	Eggink *et al*. (2022a)
Mixed feed[x]	28.7	20.6	3.4	26.2	43.4	27.0	5.1	
Brewery by-product	31.2	26.1	9.8	22.8	59.8	22.4	4.7	
Mussels	26.2	19.9	3.4	20.6	48.4	21.6	2.6	
Rapeseed cake	31.7	30.9	12.7	29.1	51.5	24.5	4.7	
Shrimp waste	20.0	37.6	7.4	21.8	49.5	22.9	4.1	

[z] DM: dry matter; CP: crude protein; CL: crude lipid. The proximate composition and chitin content were presented as the percentage of DM. A nitrogen-to-protein conversion factor of 6.25 was used for CP calculation.

[y] 70% vegetable and 30% fruit waste.

[x] Mixed feed was formulated with 66.5% water, 16.0% pea grits, 8.0% wheat, 7.0% chicken starter feed, 2.1% sugar beet pellet, and 0.4% vitamin-mineral mixture.

Due to its high content of unsaturated fatty acids, BSF fat is susceptible to oxidation during storage or feed processing, leading to reduced palatability and adverse physiological effects (Jorge Iñaki *et al*. 2022).

Protein is the most expensive nutrient and accounts for 30–50% of fish diet (Aragão *et al*. 2022). Compared to terrestrially-derived proteins, marine-based proteins offer a more balanced amino acid profile for fish but are more costly (Ma *et al*. 2020). High-quality FM generally contains 60–72% crude protein but remains only 6–10% of crude lipid (Cho & Kim 2011). To replace FM in fish diet, insufficient protein levels and deficiency in essential amino acids are the primary limitations for BSF protein. In commercial feed production, oil is generally coated after pelleting to prevent oxidation from high temperatures during extrusion (Chaabani *et al*. 2020). Therefore, the development of defatting and amino acid manipulation technologies is recommended to enhance the quality of BSF protein.

Amino acids

The essential amino acids in fish, namely arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine, are pivotal for growth and metabolism (Xing *et al*. 2024). The essential amino acid profile of various insect meals is presented in Table 2. Compared with FM, the essential amino acid index (EAAI) of BSF, cricket, and mealworm are 1.01, 0.89, and 0.58, respectively, indicating that BSF has a relatively balanced amino acid profile than others. The chemical score of BSF shows that arginine is the first limiting amino acid, followed by isoleucine, lysine, and methionine.

Soybean meal is a conventional plant-based protein source and has been successfully used as an FM alternative in various fish diets (Zhou *et al*. 2005; Lim *et al*. 2011; Yang *et al*. 2011). However, the primary limiting amino acid of soybean meal is methionine, with a chemical score of only 0.51. Methionine is also insufficient in BSF. Additionally, using crystalline amino acids is low in fish (Dabrowski *et al*. 2010). Therefore, the methionine content in BSF is a critical factor in determining its suitability for replacing FM.

Cystine is not an essential amino acid as it can be synthesized from methionine. Therefore, a sufficient dietary intake of cysteine can spare methionine (Twibell *et al*. 2000). Recent study demonstrated that there was a positive linear regression between methionine content in BSF larvae and rearing time, while no linear regression was observed in BSF larvae cysteine concerning rearing time. Moreover, elevating the carbon-to-nitrogen (C/N) ratio in almond hulls also facilitated methionine accumulation in BSF larvae but did not affect their cysteine content (Miner *et al*. 2022). This result indicates that the methionine content in BSF larvae can be manipulated by feeding substrates. However, the unchanged cysteine content suggests that the biosynthesis pathway of BSF may differ from that of vertebrates.

Fatty acid

Lipids are the most energy-dense macronutrient (9 kcal g^{-1}) and can effectively reduce protein loss by catabolism (Thirunavukkarasar *et al*. 2022). As shown in Table 3, the predominant fatty acid in BSF is lauric acid (C_{12} : 0). When the rapeseed oil was replaced with BSF oil in the Atlantic salmon (*Salmo salar*) diet, the apparent digestibility coefficients of lauric acid reached 95% and higher. In comparison, approximately only 50% of ingested lauric acid was recuperated in the tissues, indicating lauric acid is highly oxidized for energy generation. In addition, the high level of lauric acid in the BSF-based diets prevented fish liver from excessive lipid storage, which reflects metabolism dysfunction (Belghit *et al*. 2019b). These results showed that lauric acid derived from BSF is a potential protein sparer.

Furthermore, lauric acid possesses a broadly antimicrobial ability against various fish pathogens and can alleviate the inflammation induced by a bacterial infection (Huang *et al*. 2014; do Couto *et al*. 2021). Supplementing diets

Table 2. Amino acid profile of fishmeal (FM), soybean meal, and various insect meals.

Amino acid profile	FM[z]	Soybean Meal[y]	BSF[x]	Cricket[w]	Mealworm[v]
g 16 g^{-1} nitrogen					
Arginine	7.86	7.23	4.93	6.20	3.61
Histidine	1.84	2.53	3.30	2.20	1.60
Isoleucine	6.12	4.54	4.17	3.75	2.51
Leucine	6.85	7.78	6.94	6.70	4.22
Lysine	8.18	6.38	5.68	5.14	3.03
Methionine	2.49	1.26	1.84	2.02	1.15
Phenylalanine	3.55	4.94	4.13	4.00	2.51
Threonine	4.00	3.86	3.98	3.88	2.42
Tryptophan	0.72	1.28	1.63	0.85	0.57
Valine	5.33	4.80	5.85	4.24	3.62
Chemical score[u]					
Arginine	-	0.92	0.63	0.79	0.46
Histidine	-	1.38	1.79	1.20	0.87
Isoleucine	-	0.74	0.68	0.61	0.41
Leucine	-	1.14	1.01	0.98	0.62
Lysine	-	0.78	0.69	0.63	0.37
Methionine	-	0.51	0.74	0.81	0.46
Phenylalanine	-	1.39	1.16	1.13	0.71
Threonine	-	0.97	1.00	0.97	0.61
Tryptophan	-	1.78	2.26	1.18	0.79
Valine	-	0.90	1.10	0.80	0.68
EAAI[u]	-	0.99	1.01	0.89	0.58

[z] Whole herring meal (Boge 1960). FM was used as the reference protein.
[y] Egyptian soybean (Saleh 2020).
[x] Black soldier fly (BSF) prepupae fed with chicken feed (Spranghers *et al*. 2017).
[w] *Gryllus bimaculatus* (Taufek *et al*. 2018).
[v] *Tenebrio molitor* (Wu *et al*. 2020).
[u] Chemical score and essential amino acid index (EAAI) were calculated according to Kirimi *et al*. (2020).

with lauric acid (0.1% and 0.8%) in black sea bream (*Acanthopagrus schlegelii*) improved the growth performance, antioxidative capability, and intestinal morphology and microbiota of fish (Ullah *et al*. 2022). Similarly, replacing 25% of soybean oil with BSF oil facilitated the growth performance of Nile tilapia (*Oreochromis niloticus*) fry without compromising the fish body's fatty acid profile or hematological homeostasis (Goda *et al*. 2024).

However, arachidonic acid (ARA, C_{20} : 4n - 6), eicosapentaenoic acid (EPA, C_{20} : 5n - 3), and docosahexaenoic acid (DHA, C_{22} : 6n - 3), which are essential fatty acids for fish, are deficient in BSF. Since ARA is abundant in poultry meat (2.4–10.4%) (Kawashima 2019), the deficiency of ARA in BSF can be addressed through supplementation with poultry meal. By contrast, EPA and DHA are mainly originated from the aquatic ecosystems (Gladyshev *et al*. 2013). These fatty acids are generally deficient in land plants and poultry. Consequently, EPA and DHA are the primary limiting factors in meeting the essential fatty acid requirements of fish. Several studies have validated that replacing FM with BSF meal leads to poor EPA

Table 3. Fatty acid profile of cod liver oil, soybean oil, and black soldier fly (BSF).

% of total identified fatty acid	Cod liver oil[z]	Soybean oil[y]	BSF[x]
10 : 0	N.D.[w]	N.D.	1.58
12 : 0	N.D.	N.D.	46.39
14 : 0	6.38	0.08	7.85
14 : 1n - 5	N.D.	N.D.	0.53
16 : 0	19.09	11.49	12.21
16 : 1n - 7	8.75	N.D.	5.56
18 : 0	4.76	4.11	1.61
18 : 1n - 9	21.09	23.73	10.59
18 : 2n - 6	4.74	55.61	12.46
18 : 3n - 3	0.98	4.97	0.99
20 : 1n - 9	2.16	N.D.	N.D.
20 : 2n - 6	0.35	N.D.	N.D.
20 : 3n - 6	0.21	N.D.	N.D.
20 : 4n - 6	0.85	N.D.	N.D.
20 : 4n - 3	1.41	N.D.	N.D.
20 : 5n - 3	9.68	N.D.	0.23
21 : 0	1.11	N.D.	N.D.
22 : 5n - 3	4.45	N.D.	N.D.
22 : 6n - 3	14.00	N.D.	N.D.
SFA[w]	31.34	15.68	69.64
MUFA[w]	32.00	23.73	16.68
PUFA[w]	36.67	60.59	13.68
n - 3	30.52	4.97	1.22
n - 6	6.14	55.61	12.46
n - 3/n - 6	4.97	0.09	0.10

[z] Data from Francis *et al*. (2006).
[y] Data from Ferreira *et al*. (2016).
[x] BSF prepupae fed with wheat bran (El-Dakar *et al*. 2020).
[w] N.D.: not detected; SFA: saturated fatty acids; MUFA: monounsaturated fatty acid; PUFA: polyunsaturated fatty acids.

and DHA accumulation in fish bodies (Mancini *et al*. 2018; Guerreiro *et al*. 2020; Oteri *et al*. 2022; Takakuwa *et al*. 2022). Clinical signs of essential fatty acid deficiency in fish include poor growth rate, increased mortality, fin erosion, myocarditis, and sensitivity to stress (Glencross 2009). Besides animal welfare, essential fatty acids are crucial to product quality. EPA and DHA are common indicators to assess the nutritional value of seafood (Chen & Liu 2020). Moreover, a recent study found that salmon fed low levels of EPA and DHA had higher metabolic rates of astaxanthin and poor fillet color (Ytrestøyl *et al*. 2023).

Overall, BSF contains a predominant amount of lauric acid with various biofunctions but lacks EPA and DHA. Therefore, feed formulations should be designed based on the nutritional requirements of fish. In general, marine fish lack the ability to convert short-chain polyunsaturated fatty acids (PUFA) to long-chain PUFA; by contrast, freshwater fish can utilize n - 3 and n - 6 C-18 PUFA to synthesize more highly unsaturated long-chain PUFA. Consequently, marine fish have a higher requirement for n - 3 long-chain PUFAs than freshwater fish (Glencross 2009). For instance, dietary BSF-based diet resulted in the lower accumulation of n - 3 long-chain PUFAs in various marine fish, such as meagre (*Argyrosomus regius*), gilthead sea bream (*Sparus aurata*), and red sea bream (*Pagrus major*) (Guerreiro *et al*. 2020; Oteri *et al*. 2022; Takakuwa *et al*. 2022). Comparatively, completely replacing fish oil (FO) with BSF oil did not compromise the DHA content in the flesh of red hybrid tilapia (*Oreochromis* sp.) (Abu Bakar *et al*. 2021).

Chitin

Chitin is a linear polymer consisting of N-acetylglucosamine units linked by β-1,4 glycosidic bonds and presents in the exoskeleton of insects (Shamshina *et al*. 2019). As shown in Table 1, the chitin content is in the range of 1.4–8.7%. The Kjeldahl method is a widely used technique for determining the crude protein content. It estimates nitrogen content, which is then converted to crude protein content using a conversion factor. Because chitin is a nitrogen-containing compound, the crude protein of BSF meal may be overestimated when a general factor of 6.25 is used. Considering nitrogen from the chitin and other non-protein compound, conversion factors are corrected to 4.76, 4.21–5.01, and 4.47 by Janssen *et al*. (2017), Belghit *et al*. (2019a) and Smets *et al*. (2021), respectively.

Although most fish have been shown to possess chitin-degrading enzymes, their utili-

zation of chitin varies among species. Dietary 2.5–10.0% of the chitin extracted from crab shells promoted the non-specific immunity of gilthead seabream (*Sparus aurata*), including natural haemolytic complement activity, respiratory burst activity, and natural cytotoxic activity, without any negative effect on the growth performance (Esteban *et al*. 2001). By contrast, both chitin and chitosan retarded the growth performance of hybrid tilapia (*O. niloticus* × *O. aureus*) at the inclusion levels between 2–10% (Shiau & Yu 1999). In rainbow trout (*Oncorhynchus mykiss*), the tolerance of chitin derived from shrimp shells was 3%. Excessive chitin inclusion led to growth inhibition and reduced nutrient digestibility (Pascon *et al*. 2024).

Short-chain fatty acids (SCFAs), such as acetate, propionate, and butyrate, are the predominant products of bacterial chitin degradation and contribute to fish intestinal health. Therefore, chitin can potentially serve as a prebiotic in fish diets (Hasan *et al*. 2023). However, the source of chitin is a crucial factor in bioavailability. Recent studies have revealed that insects are a superior chitin source compared to crustaceans. Dietary pupal BSF exuviae meal had greater effects on intestinal SCFA-producing bacteria and SCFA production compared to shrimp head meal in rainbow trout (Rimoldi *et al*. 2023). Similarly, in largemouth bass (*Micropterus salmoides*), dietary chitin derived from both BSF and shrimp exerted positive effects on antioxidant status, non-specific immunity, intestinal microbiota, and SCFA production; however, only BSF chitin further improved growth performance and monounsaturated fatty acid deposition in muscle tissue (Hu *et al*. 2025).

Despite its prebiotic effects, chitin has also been reported to exhibit anti-nutritional properties in fish diets (Eggink *et al*. 2022b). An *in vitro* two-step enzymatic assay using pepsin and trypsin-enriched pancreatin revealed that the crude protein digestibility of BSF meal was negatively correlated with the chitin content, which was the primary variable identified in the stepwise analysis (Marono *et al*. 2015). Therefore, further studies to investigate the effect of BSF chitin on different fish species and to establish their tolerance dietary level are recommended.

IMPROVEMENT STRATEGY

Defatting

The high lipid content and abundance of unsaturated fatty acids in whole insect meal make it prone to oxidation, which reduces its palatability. Therefore, defatting is an effective process to stabilize the quality of BSF meal (Henry *et al*. 2015). When the BSF meal was used as an FM alternative in the gilthead seabream diet, the defatted meal was more readily accepted by fish than the full-fat meal (Karapanagiotidis *et al*. 2023). The defatting process is also beneficial to fish growth. Replacing FM at an isoproteic level with an adjusted fatty acid profile, the removal of the fat fraction from BSF meal improved the growth of yellowtail (*Seriola quinqueradiata*), indicating that factors in BSF oil other than fatty acids affect growth (Ido *et al*. 2021). Similarly, when 14% of FM protein was replaced in a turbot (*Scophthalmus maximus*) diet, full-fat BSF meal retarded growth performance and altered intestinal microbiota composition by increasing the abundance of potential pathogenic bacteria, whereas defatted BSF meal did not compromise these aspects and showed similarity to the FM-based diet (Zhao *et al*. 2023).

The conventional defatting processes of insect meal are divided into chemical and mechanical methods. Chemical defatting uses organic solvents, such as ethanol, acetone, and hexane, to remove insect oil. Although chemical defatting can achieve oil recovery, the residual organic solvents result in environmental or hygienic concerns (Kim *et al*. 2022). Mechanical defatting extracts oil using screw and hydraulic press in small-scale and mass production, respectively. Without pre-heating,

cold-pressing directly mechanical presses the ingredient where the temperature only rises to 50–60℃ for a short time (Leming & Lember 2005).

Comparing the quality of BSF meal defatted using chemical (aqueous, acetone, ethanol, and hexane) extraction and mechanical (cold-pressing) defatting methods, the cold-pressing showed higher total essential amino acid content and emulsifying capacity than chemical extraction (Kim *et al*. 2022). Likewise, BSF meal defatted with the mechanical method had higher digestibility of lipids, leucine, and arginine than a chemical method in hens (Xin *et al*. 2024). In terms of BSF oil, pressing and supercritical carbon dioxide extraction led to lower peroxide value than hexane after extraction (Hurtado-Ribeira *et al*. 2023). Overall, these studies indicated that the mechanical method is superior to the chemical to produce defatted BSF meal and BSF oil.

Enrichment

Rearing BSF with single substrates generally results in nutrient deficiency (Raksasat *et al*. 2020). To improve nutrient deficiency, several enrichment approaches have been studied recently. Substituting 40% of commercial laying hen feed with FM resulted in the EPA and DHA content of BSF larvae reaching a maximum level of 0.8% and 1.9%, respectively, after 3 h of enrichment. Moreover, the peak in their crude protein content (increased from 36.7 to 55.2%) was observed after 24 h (Barroso *et al*. 2017). BSF larvae reared on a fish-based substrate (soybean meal and marine fish offal) were enriched in EPA and DHA (2.2% and 0.4%, respectively), resulting in better growth in Nile tilapia compared to unenriched BSF meal when used as a replacement for FM and FO (Agbohessou *et al*. 2024). A similar result was also reported in rainbow trout, in which fish offal-enriched BSF meal, but not unenriched BSF meal could replace FM up to 50% without causing growth inhibition (Sealey *et al*. 2011). In addition, the inclusion of 25% fish waste in banana and orange peels resulted in a 2.7-fold increase in biomass conversion efficiency, indicating that co-composting plant and fish byproducts can not only improve nutrient availability but also reduce the production cost of BSF meal (Isibika *et al*. 2021).

Algae are the predominant producers of EPA and DHA in aquatic ecosystems. The brown seaweed (*Ascophyllum nodosum*) was used to replace the basic feeding medium at levels ranging 0% to 100%. The EPA content of BSF larvae was positively correlated with the dietary level of brown seaweed. However, it is worth noting that dietary brown seaweed negatively affected the growth performance of BSF (Liland *et al*. 2017). Furthermore, since seaweed can accumulate heavy metals from the environment, the cadmium and total arsenic levels in BSF larvae exceeded the maximum residue limits set by the European Union when the dietary level of brown seaweed exceeded 20% (Biancarosa *et al*. 2018).

Rearing BSF larvae on chicken manure, brewers' spent grain, and kitchen waste modified their arginine, glutamic acid, proline, tyrosine, and phenylalanine, whereas no effect was detected on the most limiting amino acids, such as lysine, methionine, isoleucine, and tyrosine (Shumo *et al*. 2019). Another study showed that lysine, valine, and leucine were the most altered amino acids in BSF larvae when fed different vegetable by-products (Fuso *et al*. 2021). A single amino acids reduction trial demonstrated that reducing 65% of each amino acid did not affect the growth performance of BSF larvae. Moreover, balance calculations for individual amino acids revealed that deficiency of amino acids was compensated through substrate microbiome synthesis (Lemme & Klüber 2024).

As discussed in Section Amino acid, methionine content in BSF is a critical limiting amino acid for FM replacement. However, to date, no study has demonstrated that BSF larvae are capable of directly accumulating methionine from methionine-enriched substrates. Extending rearing time and increasing

the C/N ratio in substrates have been proven to enhance methionine levels in BSF larvae, indicating that methionine content can be improved through methods other than direct enrichment (Miner *et al*. 2022). Moreover, since microbiota play a crucial role in amino acid synthesis in BSF substrates (Lemme & Klüber 2024), further studies are needed to identify the amino acid-synthesizing bacteria.

Removal of chitin

The fractionation of BSF typically includes dry and wet modes. The dry mode is a conventional processing method of insects, which involves drying and defatting steps. The dry mode cannot isolate chitin from the insect body and the final products are BSF oil and defatted BSF meal. By contrast, the wet mode uses a juice press step to separate the chitin-rich press cake from BSF juice. Subsequently, the BSF juice is centrifuged and divided into the lipid, cream, aqueous, and solid fractions. The composition analysis revealed that approximately 60% of the total chitin is retained in the press cake, and the remaining chitin (40%) is primarily found in the solid fraction (Ravi *et al*. 2021).

Sieving is an alternative method for fractionation. The BSF meal defatted using the pressing method was mechanically sieved into particle sizes of 0–200 μm, 200–400 μm, and > 400 μm. Their chitin contents were 18, 27, and 154 g kg^{-1}, respectively, with similar crude protein levels of 54.9%, 55.7%, and 55.9%, respectively. This result indicated that a 400 μm sieve can effectively filter out the chitin-rich fraction. However, the yield of each fraction was not provided in that study (Eggink *et al*. 2022b). To assess the feasibility of sieving for fractionation, further studies on yield and optimal particle sizes are necessary.

CONCLUSION

BSF has emerged as a promising and sustainable alternative protein source to FM in aquaculture. However, some nutritional limitations, particularly in essential amino acids (e.g., methionine), essential fatty acids (e.g., EPA and DHA), and excessive chitin must be addressed to optimize its use in aquafeeds. Strategies such as defatting, substrate enrichment, and chitin removal can enhance the nutritional quality and bioavailability of BSF meals to fish. To maximize its potential as a sustainable feed ingredient in the aquaculture industry, establishing BSF meal quality standards and conducting additional studies on species-specific dietary tolerance are necessary.

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黑水虻 (*Hermetia illucens*) 作為水產養殖永續性蛋白質原料的綜述：營養限制與改善策略

郭裔培 [1,*]　謝易叡 [2]　楊順德 [3]

摘要

郭裔培、謝易叡、楊順德。2025。黑水虻 (*Hermetia illucens*) 作為水產養殖永續性蛋白質原料的綜述：營養限制與改善策略。台灣農業研究 74(3):205–219。

魚粉是水產養殖飼料中的主要蛋白質來源，然而由於捕撈資源的限制，全球魚粉供應量已無法滿足快速成長的水產養殖產業。黑水虻 (*Hermetia illucens*) 具有將不可食用的有機副產物高效率轉化為蛋白質的能力，被認為是一種永續性的魚粉替代蛋白。然而，使用植物性基質餵養的黑水虻常存在營養限制的問題，這些營養缺口可能對魚類的生長表現、免疫反應以及魚肉品質造成負面影響。此外，幾丁質作為昆蟲外殼的主要成分，在魚類飼料中的作用尚有爭議，部分研究指出幾丁質對魚類健康有正面效益，但另有研究發現幾丁質對某些魚種具有抗營養因子的效果。本綜述評估了黑水虻粉在水產養殖飼料中的營養潛力，黑水虻的主要限制性胺基酸包括精胺酸、異亮胺酸、賴胺酸及甲硫胺酸，而主要限制性脂肪酸為 eicosapentaenoic acid (EPA) 與 docosahexaenoic acid (DHA)。為了提升黑水虻幼蟲的營養品質，本文重點分析其蛋白質含量、胺基酸組成、脂肪酸組成及幾丁質的影響，並探討了脫脂處理、基質調控以及去除幾丁質等具發展潛力的改善策略。

關鍵詞：黑水虻、水產養殖、胺基酸、脂肪酸、幾丁質。

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* 通訊作者：ipkuo@mail.ntou.edu.tw
[1] 國立臺灣海洋大學水產養殖學系助理教授。臺灣 基隆市。
[2] 農業部水產試驗所澎湖漁業生物研究中心副研究員。臺灣 澎湖縣。
[3] 農業部水產試驗所淡水養殖研究中心研究員。臺灣 彰化縣。