

PERSPECTIVES ON THE USE OF BLACK SOLDIER FLY LARVAE (*HERMETIA ILLUCENS*) IN AQUACULTURE FEED: NUTRITIONAL BENEFITS, WASTE REDUCTION, AND SUSTAINABILITY

¹Damodharan Vadivelu, ²Jagatheeswari Asaithambi

¹ Professor, Department of Civil Engineering, Annamalai University,

² Research Scholar, Department of Civil Engineering, Annamalai University, Chidambaram, Tamil Nadu, India.

Review Article

Abstract

Black Soldier Fly Larvae (BSFL) have attracted global interest due to their exceptional ability to convert organic solid waste into nutrient-rich biomass. As a key component of the circular economy, BSFL offer a sustainable solution to both waste management and protein production challenges. Their versatility in utilizing a wide range of organic substrates, including municipal solid waste, without significant mortality highlights their ecological adaptability and economic potential. During the prepupal phase, BSFL are particularly nutrient-dense, containing high-quality protein (22.97–53.00%) and lipids (24.00–47.30%), making them valuable for applications in animal husbandry, aquaculture, and biodiesel production. Their amino acid profile is comprehensive, supporting excellent bioavailability in animal diets, while the lipid content enhances energy density and industrial utility. In aquaculture, BSFL are increasingly recognized as a viable alternative to fishmeal, supporting healthy growth in various aquatic species. Their use reduces reliance on marine-based resources and contributes to more sustainable aqua feed production. BSFL represent a promising avenue for sustainable nutrient recycling and high-value protein generation. Their integration into aquaculture and animal feed systems offers significant environmental and economic benefits. However, further research is necessary to determine the optimum replacement ratios for fishmeal and to standardize rearing practices across different production scales. This will ensure the full realization of BSFL's potential in supporting waste valorization, food security, and ecological balance in the long term.

Key words: Black Soldier Fly Larvae, Sustainable protein, Organic waste bioconversion, Aquaculture feed, Fishmeal replacement.

1. Introduction

In India, aquaculture contributes around 1% of the Gross Domestic Product (GDP) while accounting for more than 5% of agricultural GDP. This industry alone provides job prospects for roughly 28 million people and surpassed 2 trillion (INR) in fiscal year 2023 [1, 2, 3]. India is the world's third-largest fish producer, accounting for around 8% of total fish production. In FY 2022-23, India reached a record fish production of 175.45 lakh tonnes. [4]. Aquaculture, or the farming of aquatic organisms such as fish, shellfish, and seaweed, plays a significant part in worldwide economic development. For example, research in Bangladesh revealed that aquaculture contributed to roughly 10% of the country's poverty reduction in the early twenty-first century. [5]. The Black Soldier Fly (BSF) is widely distributed throughout the globe; they particularly thrive in tropical and subtropical climates. However, temperature and humidity must be controlled in favour of BSF when climatic conditions are unfavourable. A controlled environment with adequate facilities is prerequisite for large-scale production. The countries in these regions are fast-growing and demand to boost their economy by implementing development policies, which in turn ultimately results in a huge volume of waste generation. BSF's are well known for their potential to convert Organic Solid Wastes (OSW) into diversified products. They can be reared a variety of organic solid wastes generated, ranging from households to different kinds of farming activities. In lower and middle-income countries, converting organic wastes into valuable resources, in the use of BSFL, the daily waste generated can be reduced up to 78.9% [6]. Poultry waste materials were successfully reduced (52.36%) using the larvae, which eventually generated protein-rich and highly nutrient by-products [7]. Wastes containing brewing residues of 75% in total weight were efficiently managed using the larvae, and higher brewing residue concentrations positive outcome on larval biomass yield [8]. The synergy of BSFL and microbiota demonstrated excellent lipid reduction present in domestic biodegradable wastes. The lipid content decreased by 95%, and seed germination increased by 20%; this combined action enhances lipid metabolism [9]. The type of rearing substrate significantly influences the larvae's waste reduction performance. Domestic waste and solid decanters were used as substrates, achieving waste reduction of 76.5% and 32.6%, respectively [10]. Wet organic solid wastes can be effectively and sustainably managed using these as substrates, especially fruit waste, which showed the highest bioconversion efficiency among a mixture of OSW [11]. Converting decanter cake and palm kernel expeller mixture into frass achieved a waste reduction rate ranging between 81% and 83%, offering a sustainable waste management approach with valuable agricultural applications. The frass enhances soil nutrients while offering an eco-friendly fertilizer alternative [12]. Defatted BSF has significantly higher protein content (47.70%) compared to full-fat BSF (30.72%), and it contains higher lipid levels (36.20%) than defatted BSF (8.11%), which makes the process

makes suitable alternative feed for aquaculture [13]. BSFL reared on chicken manure exhibited the highest mineral turnover compared with brewers' spent grain and kitchen waste; each substrate influenced the larvae's nutrient composition [14]. Nutrient analysis on prepupal stages of larvae reared on fruit wastes had higher crude protein and lipid content, rich in minerals like calcium and potassium, followed by magnesium, manganese, and zinc [15]. Replacing fish meal (FM) with insect meal (IM) (BSFL) does not affect the growth rate, feed intake, survival rates and hematological parameters on Nile tilapia [16]. Substituting FM with IM up to 60% offers a sustainable and profitable replacement for conventional feed for *Oreochromis niloticus* [17]. BSFLM for fish and shrimp expressed improved overall growth parameters [18]. Supplementation of IM with 30% for juvenile swamp eels showed the highest growth rate and survival rate, it appears a promising source of sustainable feed while addressing the challenges of FM scarcity [19]. BSFLM (BSFLM) as a substitution for African catfish (*Clarius gariepinus*) diet ranging from 75-100% showed improved growth rate, feed conversion ratios and survival compared to FM based diets, and it supports environmental sustainability [20]. BSFL offers a low-cost, high-quality aquafeed alternative. They thrive on OSW, reducing disposal costs. Rearing BSFL generates income from waste conversion. High protein content supports efficient fish growth and reduces reliance on expensive fishmeal. Improves profitability for small-scale fish farmers and encourages a circular economy in low-income countries.

This review aims to: (i) critically evaluate the nutritional composition of BSFL across a range of rearing substrates, with emphasis on substrate-driven variability; (ii) synthesise and compare species-specific growth performance data from aquaculture feeding trials; (iii) assess the waste bioconversion efficiency and broader environmental sustainability of BSFL production systems; (iv) identify existing knowledge gaps and propose future research priorities. By adopting this analytical approach, the review seeks to provide actionable insights for aquafeed formulators, aquaculture practitioners, and researchers working toward the mainstreaming of insect-derived feed ingredients.

2. Nutritional Composition of BSFL

2.1 Crude Protein and Crude Fat

Table 1: Nutritional Composition - Crude protein and fat - of BSFL (*Hermetia illucens*) reared on different organic substrates, expressed as a percentage of dry matter (%DM). Data are drawn from published peer-reviewed studies; where multiple studies are cited, values represent reported means. DM = Dry Matter.

Sl.no	Rearing Substrate	Crude protein (in % ¹ DM)	Crude Fat (in % ¹ DM)	References
1	Fruits and vegetables	22.97	28.40	[21, 22]
2	Chicken manure	41.60	34.40	[23, 14]
3	Coconut endosperm	29.70	47.30	[24]
4	Poultry Manure	41.20	28.60	[25, 26]
5	Municipal Organic Solid Wastes	40.00	38.00	[27, 28]
6	Pig manure	35.00	24.00	[29]
7	Brewers waste	42.00	34.00	[29]
8	Slaughter house wastes	53.00	25.00	[30]

Depending on rearing substrate crude protein range in threefold (22.97 -53.00%) and a two fold range in crude fat (24.00 - 47.30%). The substrate, which is a mixture of fruits and vegetables, are low in nitrogen and fat content resulting in larvae yields with lowest CP and moderate CF, consistent with the substrate's macronutrient-poor composition [21, 22]. By contrast, substrates rich in nitrogen such as slaughterhouse waste, chicken manure, and brewers grain yields larvae with higher CP accumulation - upto 53.00% in larvae reared on slaughterhouse wastes [30]. This indicates the well-established relationship that BSFL CP content strongly positively correlates with the nitrogen content present on the rearing substrate [14]. Coconut endosperm, which is rich in medium chain triglycerides, as a rearing substrate, yielded larvae with highest CF (47.30%), This explains that higher dietary lipid incorporation helps to produce BSFL that is rich in crude fat [24]. However, on the other hand, substrates that are low in fat content, such as poultry manure, manage to yield larvae with moderate to high CF (28.60 - 34.40%), likely indicative of microbial transformation of substrate organic matter during bioconversion. Even though substrates low on fat content still manage to yield larvae with high CF on body composition. It proves that dietary lipid content and larval CF is more complex. Also of note is the difference in CP and CF between full-fat and defatted BSFL fractions. Defatted BSFL meal has increased CP (~47.70%) and decreased CF (8.11%) compared to full-fat meal with 30.72% CP and 36.20% CF [13]. This processing flexibility is a major practical advantage, allowing feed formulators to adapt the protein to fat ratio to the needs of specific target species. Together, these results highlight that substrate selection is a key driver of BSFL nutritional quality and that substrate composition is an important quality control parameter that future production systems should consider. Standardised rearing protocols are urgently needed to reduce inter-batch variability and to enable reliable feed formulation

2.2 Amino Acid Profile

Table 2: Amino acid profile Amino acid profile of Black Soldier Fly Larvae (*Hermetia illucens*) meal expressed as percentage of dry matter (% DM) across three processing methods: spray-dried (SPR), oven-dried condition 1 (OVN1), and oven-dried condition 2 (OVN2). Essential and non-essential classifications follow standard nutritional nomenclature. DM = Dry Matter.

¹ DM – Dry Matter

Sl. no	Amino Acid	Classification	² SPR	³ OVN1	⁴ OVN2	References
Essential Amino Acids (EAA)						
1	Histidine	Essential	2.77	2.70	2.08	[31] [32]
2	Threonine	Essential	1.94	1.85	1.42	[31] [33]
3	Arginine	Essential	2.55	2.25	1.80	[31] [34]
4	Methionine	Essential	1.07	0.93	0.61	[31] [34]
5	Valine	Essential	3.09	2.92	2.29	[31] [33]
6	Phenylalanine	Essential	2.11	1.98	1.35	[31] [33]
7	Isoleucine	Essential	2.40	2.28	1.76	[31] [34]
8	Leucine	Essential	3.62	3.51	2.67	[31] [33]
9	Lysine	Essential	3.60	2.87	2.44	[28] [31]
Non-Essential Amino Acids (NEAA)						
10	Aspartic Acid	Non-Essential	5.09	4.55	3.30	[31] [33]
11	Glutamic Acid	Non-Essential	6.05	5.63	4.59	[31] [34]
12	Serine	Non-Essential	2.06	1.88	1.55	[31] [33]
13	Glycine	Non-Essential	0.25	0.22	0.12	[28] [31]
14	Alanine	Non-Essential	3.06	3.00	3.13	[28] [31]
15	Proline	Non-Essential	2.86	2.81	2.30	[28] [31]

Beyond protein content in BSFL, the quality of nutritional value of a protein ingredient is well defined by its amino acid composition - specifically for the requirements of target species it is necessary that an adequate amount of essential amino acids (EAA) is important. Table 2 presents the amino acid profile of BSFL meal processed by three different drying methods: spray-drying (SPR), oven-drying at condition 1 (OVN1), and oven-drying at condition 2 (OVN2) [31–34]. Table 2 reveals that BSFL meal affords a comprehensive spectrum of both essential and non-essential amino acids. Among EAA, lysine (3.60–2.44% DM) higher concentration supports growth & skeletal development, higher concentration of lysine essential for bone matrix and skeletal development of finfish. To construct Branched-Chain Amino Acids (BCAAs) Leucine (3.62–2.67% DM) and Valine (3.09–2.29% DM), along with isoleucine (2.40 - 1.76%) are abundantly present on BSFLM, these amino acids critical for protein synthesis and build muscle tissue. In order to maintain metabolic balance during a stressful activity such as feed transition it acts as a nitrogen contributor. Valine prevents muscle degradation while improving protein accumulation, boosts digestive enzyme performance and has an antioxidant property which diminishes oxidative stress [28,31,33,34]. Histidine and arginine also show appreciable levels (2.77–2.08% and 2.55–1.80%, respectively, essential for immune function and nitrogen metabolism [31,32,34]). Notably low concentrations of Methionine (1.07–0.61% DM) compared to fishmeal indicates supplementation in formulations on targeting species with high sulphur amino acid requirements, such as salmonids [34]. Careful consideration is required when formulating fishmeal based on black soldier fly larvae meal (BSFLM). Among non-essential amino acids, glutamic acid (6.05–4.59%) and aspartic acid (5.09–3.30%) are the most predominant, reflecting their roles in cellular metabolism and neurotransmission [31,33,34]. Alanine (3.06–3.13%) and proline (2.86–2.30%) are also significant, which are important in energy metabolism and collagen synthesis, respectively [28,31]. It is acknowledged from Table 2 is the significant reduction in amino acid concentrations between spray dried and oven dried conditions, indicates that thermal processing greatly reduce the presence of amino acid - especially for heat-sensitive amino acids such as lysine, which is prone to Maillard reaction-induced losses in the course of high temperature drying. This limitation should be explicitly acknowledged when designing BSFLM-based diets.

2.3 Lipid Profile

Table 3. Lipid composition of Black Soldier Fly Larvae (*Hermetia illucens*) prepupae expressed as grams per 100 g dry matter (g/100g DM, %). Values include total lipid content, major fatty acid classes, individual fatty acid fractions, and the omega-6 to omega-3 ratio (ω-6:ω-3). DM = Dry Matter.

Sl. no	Parameters	Value (g/100g DW in % ⁵ DM)	References
1	Total Lipid content	35.00	[35]
2	Saturated Fatty acids (SFA)	60.00	[36]
3	Lauric Acid (C12:0)	45.00	[37]
4	Myristic acid (C14:0)	10.00	[38]
5	Palmitic acid (C16:0)	12.00	[39]
6	Monounsaturated Fatty Acids (MUFA)	18.00	[40]
7	Oleic acid	15.00	[41]
8	Polyunsaturated Fatty Acids (PUFA)	10.00	[42]
9	Linoleic acid (C18:2 ω-6)	8.00	[43]
10	α-Linolenic acid (C18:3 ω-3)	2.00	[44]
11	ω-6:ω-3 Ratio	10:1	[45]

² SPR – Spray Dried

³ OVN1 – Oven Dried 1

⁴ OVN2 – Oven Dried 2

⁵ DM – Dry Matter

The lipid composition shown in Table 3 provides valuable insight into the nutritional quality and functional characteristics of the studied fat source. The total lipid content is notably high at 35.00 g/100g dry matter (DM), indicating a rich source of energy and essential fatty acids [35]. Among the fatty acid classes, saturated fatty acids (SFA) dominate the profile, accounting for 60.00% of the total lipid content [36]. The most abundant SFA is lauric acid (C12:0) at 45.00%, followed by palmitic acid (C16:0) at 12.00%, and myristic acid (C14:0) at 10.00% [37] [38] [39]. High lauric acid content suggests antimicrobial potential [37]. Monounsaturated fatty acids (MUFA) contribute 18.00%, primarily composed of oleic acid (15.00%), which is known for its cardiovascular benefits and oxidative stability [40] [41]. Polyunsaturated fatty acids (PUFA) make up 10.00% of the total lipids, with linoleic acid (C18:2 ω-6) at 8.00% and α-linolenic acid (C18:3 ω-3) at 2.00% [42] [43] [44]. Although PUFA levels are lower than SFA, the presence of both omega-6 and omega-3 fatty acids contributes to anti-inflammatory and immune-supporting roles. The ω-6:ω-3 ratio is reported as 10:1, which, although higher than the optimal dietary ratio (~4:1 or lower), is within acceptable limits for certain feed and industrial applications [45]. Overall, the lipid profile in Table 3 indicates a fat source with high energy value, a predominance of saturated fatty acids, and a useful balance of unsaturated fats.

3. BSFL as a sustainable alternative to Fishmeal in aquaculture

Table 4. Summary of BSFL meal (BSFLM) inclusion in aquaculture diets across commercially important aquatic species, showing the optimal or maximum tested inclusion level and key growth performance outcomes. FCR = Feed Conversion Ratio; CP = Crude Protein.

Species	Optimal BSFLM Inclusion Level	Key Outcome	References
<i>Nile tilapia (Oreochromis niloticus)</i>	Up to 100%	Equal or superior	[16, 17, 46]
<i>Common carp (Cyprinus carpio)</i>	Up to 75%	Higher growth; CP 20.23%	[47, 48]
<i>Pacific white shrimp (Litopenaeus vannamei)</i>	Up to 25%	Comparable to fishmeal	[49, 50]
<i>Atlantic salmon (Salmo salar)</i>	Up to 25%	Reduced growth performance	[51]
<i>Snakehead fish (Channa striata)</i>	Up to 50%	Improved growth and feed efficiency	[52]
<i>Red hybrid tilapia (Oreochromis spp.)</i>	Up to 30%	Best growth performance	[53]
<i>Siamese fighting fish (Betta splendens)</i>	Up to 13%	Enhanced growth parameters	[54]
<i>Siberian sturgeon (Acipenser baerii)</i>	Partial	Economically profitable; gut development improved	[55]
<i>Redclaw crayfish (Cherax quadricarinatus)</i>	Partial	Enhanced immunity and antioxidant activity	[56]
<i>Juvenile swamp eel (Monopterus albus)</i>	30%	Highest growth and survival rates	[19]
<i>African catfish (Clarias gariepinus)</i>	75–100%	Improved FCR and survival	[20]

Research indicates that Nile tilapia (*Oreochromis niloticus*) fed with BSFLM (up to 100%) exhibit superior growth performance compared to conventional fish meal. [46]. A 75-day trial conducted on common carp (*Cyprinus carpio*) supplementing traditional

fish meal with BSFL as a substitution at different levels (up to 75%) showed a higher growth rate, achieved 20.23% crude protein and lipid content ranges up to 4.64% [47, 48]. Studies suggests that replacing of pacific white shrimp (*Litopenaeus vannamei*) diet up to 25% with BSFL exhibited equal performance compared with traditional fishmeal [49, 50]. Atlantic salmon (*Salmo salar*) diet on BSFLM up to 25% resulted in reduced growth [51]. The inclusion of fresh or dried BSFLM up to 50% in Snakehead fish (*Channa striata*) showed improved growth performance and feed efficiency [52]. Red hybrid tilapia (*Oreochromis spp.*) diet inclusion of BSFLM up to 30%, exhibit best growth performance [53]. A study conducted on Siamese fighting fish (*Betta splendens*), diet inclusion of BSFLM up to 13% showed enhanced growth parameters [54]. Supplementation or replacing traditional FM with BSFL had significantly reduced the fish-in-fish-out (FIFO) ratio, contributing to sustainable aquaculture practices [55]. Redclaw Crayfish (*Cherax quadricarinatus*) fed with BSFLM exhibit enhanced immunity and antioxidant activity [56].

3.2 Feeding Strategies and Formulation Considerations

Successful incorporation of BSFLM into commercial aquafeeds would need to address not only the simple substitution of fishmeal protein but also the formulation strategies employed. Various parameters that could affect the utilization efficiency and palatability of BSFLM include (i) processing techniques such as full-fat vs. defatted meal, fresh vs. dried, and meal vs. paste that have a major impact on the pellet properties, oxidative stability, and digestibility of the nutrients; (ii) presence of chitin, whose levels vary depending on the development stages of the larvae and degree of deshelling, affecting gut passage and possibly protein digestibility of sensitive species; (iii) the lauric acid content, which is an active nutrient that can affect microbiome structure if fed in high amounts; and (iv) dietary amino acid composition and supplementation, especially LC-PUFA. Another formulation strategy which is being developed at present is combining BSFLM with other complementary components, such as BSFLM (providing protein), along with algal/fish oil supplementation (addressing the issue of LC-PUFA deficiency) and plant proteins rich in methionine (compensating for sulfur amino acid deficiency). Such formulations of multiple components have been shown to provide more fishmeal replacement levels with nutritionally complete diets for several different species.

4. Waste Bioconversion and Circular Economy Integration

In addition to its nutritional importance as larval biomass, the bio-economy cycle value of BSFL includes its ability to treat various organic waste streams biologically in an effective manner. The daily mass of organic solid waste treated with BSFL can be reduced by 78.9% [6], depending upon the nature of the substrate. Household wastes and solid decanters provide reductions of 76.5% and 32.6% respectively [10], whereas the highest reduction of bioconversion efficiency was obtained using fruit wastes in comparison to other kinds of mixed organic solid waste substrates [11]. Reduction of decanter cake/palm kernel expeller mixes was 81%-83% when used as BSFL substrates [12]. Valorization of high nitrogen substrates including poultry manure and brewers spent grain has been achieved using BSFL, in which poultry waste has been successfully reduced by 52.36% through production of protein enriched larval biomass [7]. The combined effect of BSFL activity with the existing microbes within domestic biodegradable waste material has successfully led to the reduction of lipid content of the substrate by up to 95% along with 20% improvement in germination index of seedlings grown using the residue frass material, suggesting higher quality of the produced compost material [9]. In mixed waste bioconversions involving livestock waste and wet distiller grains, BSFL was highly efficient in converting difficult organic materials into simpler components while decreasing ammonia and volatile fatty acid release [57, 58].

BSFL conversion results in frass, which can be used as valuable soil amendments. Frass from BSFL bioconversions contains abundant levels of chitin – a structural polysaccharide that can trigger immunity in plants while reducing soil-borne pathogens – in addition to nutrients like nitrogen, phosphorus, and potassium. The agricultural benefits of BSFL frass have been proven in numerous plant types, making BSFL frass an added value component that makes BSFL waste processing economically viable. It is important to note that BSFL bio-conversion technology provides a way of managing organic wastes that suits low and middle-income nations located in tropical and subtropical zones; in other words, the very places that have been witnessing increased growth in aquaculture and the resultant increase in organic waste and inadequate waste treatment facilities. Having BSFL and fish farms located together leads to a sustainable system whereby the fish farm organic waste is fed to the larvae, which in turn nourish the fish.

5. Sustainability and Environmental Benefits

Studies of BSFL rearing on a mixture of organic solid wastes combined with livestock manure can efficiently convert wastes into valuable by-products in a sustainable method [57, 58]. The anaerobic decomposing process of organic wastes in landfills releases high amounts of greenhouse gases into the atmosphere. Treating organic waste with BSFL reduces methane emission. BSFL rearing requires less land space compared to traditional waste management systems like composting or landfill expansion [59]. In sustainable waste management, user-friendly bins can be accommodated to rear BSFL as a practice of localized waste treatment [60]. Sludge-fed BSFL used for biodiesel production reduces greenhouse gas emissions by up to 100 times compared to sludge landfilling [61]. BSFL biodiesel production emits fewer greenhouse gases compared to other feedstock, which enables a low carbon footprint [62]. The residual biomass after lipid extraction can be used as protein-rich feed or fertilizer, creating a closed-loop system that minimizes environmental impact [63, 64]. BSFL can accumulate heavy metals from their feed, and levels remain below legal limits for human consumption [65]. Production of BSFL requires less land and water compared to soybean meal or fishmeal, a sustainable alternative [66].

6. Challenges and Knowledge Gaps

Even though BSFL have been proven highly promising as a potential aquafeed additive, there remain many issues which require resolution before this technology can be used extensively for commercial purposes.

Nutritional variability and standardization: The wide nutritional variability between different batches of BSFL based on various substrates, different life stages, and processing techniques is one of the major problems preventing the development of efficient aquafeed formulations. In the absence of standardizing processes of BSFL production and processing, it becomes impossible for feed companies to estimate the nutrient content of the ingredient.

Anti-nutritional factors: In sensitive species presence of Chitin, lectins and other available exoskeletal components in whole BSFLM may considerably impair digestibility and gut microbiota. enzymatic pre-treatment, deshelling and fermentation may alleviate the undesired effects, limiting the bio-availability of macro and micro nutrients.

PUFA deficit: In the absence of LC-PUFAs such as EPA and DHA in BSFL fats, the application of BSFL meal (BSFLM) as a sole replacement for fishmeal to raise carnivores is difficult, especially for fish from the salmonid family. Substrate enrichment approaches that focus on elevating the concentrations of LC-PUFAs in larval fats have been tested under laboratory conditions; however, their efficacy in commercial production systems needs verification.

Long-term and multi-endpoint feeding trials: The primary focus of the majority of published feeding trials are growth rate and feed conversion ratio and are of limited duration, typically ranging from 60-90 days. long term data on reproductive performance, survivability, fillet quality and immune competence across production cycles remain scarce.

Regulatory frameworks: In major aquaculture - producing countries, like India, there still lacks a holistic regulatory pathway for insect - based feed ingredients, This creates an uncertainty that deters commercial investment. The regulatory status of BSFL derived feed ingredients varies significantly across country jurisdictions. The European Union has progressively given approval to exercise insect meal for use in aquafeed.

Economic feasibility at commercial scale: Most economic evaluations of BSFL farming have been done on smaller or pilot scale projects. A techno-economic evaluation that considers the cost of raw materials sourcing, farm establishment and maintenance, labor, processing, quality control and transportation costs will be necessary to evaluate the conditions where BSFL meals (BSFLM) would be able to compete against fishmeal economically.

Lack of Awareness among farmers: General public awareness of BSFLM's potential in aquaculture may hinder income-generating opportunities. Adopting low-cost fishmeal production reduces farmers' financial burden by significantly decreasing dependence on commercial aquafeed products. Further, unlike other aquaculture practices that involve intensive labour from the production of BSFLM from commencement to the end product, it requires only minimal human resources, resulting in an overall reduction in manufacturing costs and increased revenue.

7. Conclusion and Future Directions

Black Soldier Fly Larvae (BSFL) have emerged as a promising sustainable alternative protein and lipid source for animal nutrition, particularly in aquaculture. The nutritional profile of BSFL is characterized by a high content of essential amino acids such as leucine, lysine, and valine, which are critical for growth and metabolic functions. Additionally, BSFL exhibits a rich lipid composition, dominated by medium-chain saturated fatty acids like lauric acid, and supplemented with beneficial monounsaturated and polyunsaturated fatty acids. These characteristics make BSFL an excellent candidate to partially or fully replace conventional feed ingredients like fish meal and fish oil. Despite the growing body of evidence supporting the nutritional adequacy and functional benefits of BSFL, further research is warranted to determine the optimal inclusion levels for various fish species and production stages. In conclusion, BSFL offer a sustainable and nutrient-rich alternative for fish feed, but comprehensive, species-specific studies are essential to optimize their use as a complete or partial replacement for fish meal in commercial aquaculture. However, there are still several key limitations associated with BSFLM. Firstly, the insufficient content of EPA and DHA, the variable nutritional profile because of substrate and processing used, and the existence of some anti-nutritional compounds like chitin limit the universal use of BSFLM among various aquatic organisms. In particular, these aspects seem especially relevant for salmonids nutrition, since LC-PUFAs addition and careful use of partial inclusion strategy appear to be inevitable steps.

The research directions should include: (i) comprehensive multi-species dose-response studies that combine data on growth, gut histology, microbiome analysis, and effects on reproductive performance; (ii) methods of substrate improvement intended to increase the LC-PUFA levels in the larval lipid composition at large-scale industrial conditions; (iii) techno-economic and lifecycle assessments of BSFL rearing systems integrated into the aquaculture production value chains across different geographical and economic contexts; (iv) development of rapid and inexpensive techniques for BSFL quality evaluation for the purpose of industry standardization; and (v) engagement with the regulators to develop science-based approval procedures for the use of insect products as animal feeds in aquaculture in major producing countries. To fully capitalize on the potential of BSFL in modern aquafeed production systems will require collaborative work of researchers, industry practitioners, and policymakers. However, given the results reviewed in this paper, it is safe to be confident about the prospects of the topic.

List of abbreviations:

BSF: Black Soldier Fly | BSFL: Black Soldier Fly Larvae | BSFLM: Black Soldier Fly Larvae Meal | CP: Crude Protein | CF: Crude Fat | DM: Dry Matter | DHA: Docosahexaenoic Acid | EAA: Essential Amino Acids | EPA: Eicosapentaenoic Acid | FCR: Feed Conversion Ratio | FIFO: Fish-In-Fish-Out ratio | FM: Fishmeal | FY: Fiscal Year | GDP: Gross Domestic Product | GHG: Greenhouse Gas | INR: Indian Rupees | LC-PUFA: Long-Chain Polyunsaturated Fatty Acids | LCA: Lifecycle Assessment | MOSW: Municipal Organic Solid Waste | MUFA: Monounsaturated Fatty Acids | NEAA: Non-Essential Amino Acids | OSW: Organic Solid Waste | OVN1/OVN2: Oven-Dried conditions 1 and 2 | PUFA: Polyunsaturated Fatty Acids | SFA: Saturated Fatty Acids | SPR: Spray-Dried

Declarations

Consent for Publication

All authors have given their full consent for the publication of this manuscript.

Ethics Declaration

Not applicable.

Conflicts of Interest

The authors declare that they have no conflict of interest related to the subject matter of this manuscript.

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Data Availability

The data supporting the findings of this review are available within the article and its reference.

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Authors Contributions

DV conceptualized and prepared the research work, including the review and manuscript writing. JA provided support in literature collection, data organization, and assisted in manuscript refinement. Both authors reviewed and approved the final version of the manuscript.

References

- [1] Kakra A. Economic impact of aquaculture development in India. Forvis Mazars; 2023.
- [2] Government of India. Ministry of Agriculture and Farmers Welfare. New Delhi; 2019.
- [3] FAO. Fishery and Aquaculture Profiles: India. Food and Agriculture Organization of the United Nations; 2022.
- [4] Ministry of Fisheries, Animal Husbandry and Dairying. Year End Review 2023: Department of Fisheries. PIB, Delhi; 2023.
- [5] Gonzalez Parrao C, et al. Aquaculture for improving productivity, income, nutrition and women's empowerment in low- and middle-income countries: a systematic review and meta-analysis. *Campbell Systematic Reviews*. 2021;17(4).
- [6] Diener S, et al. Biological treatment of municipal organic waste using black soldier fly larvae. *Waste Biomass Valorization*. 2011;2(4):357–363.
- [7] Niranjana BH, et al. Bioconversion and performance of black soldier fly (*Hermetia illucens*) in converting organic poultry waste materials into high-value products and fertilizers. *Waste and Biomass Valorization*. 2024;15:5559–5572.
- [8] da Costa e Silva D, et al. Performance of larvae of the black soldier fly (*Hermetia illucens*) in the bioconversion of brewery waste. *Waste and Biomass Valorization*. 2024;15(4):1–8.
- [9] Jiang S, et al. Insights on lipid biodegradation in domestic biodegradable waste at a full-scale black soldier fly larvae bioconversion. *Waste and Biomass Valorization*. 2024;15:6021–6034.
- [10] Rohmanna NA, et al. Waste reduction performance by black soldier fly larvae on domestic waste and solid decanter. *Biotropica: Journal of Tropical Biology*. 2022;10(2).
- [11] Karthikeyani KT. The efficiency of black soldier fly larvae with vegetable, fruit and food waste as a biological tool for sustainable management of organic waste. *International Journal of Environment and Climate Change*. 2024;14(2):441–448.
- [12] David CS, et al. Waste reduction rate, agronomic properties, and effect on bekenu series soil pH buffering capacity of black soldier fly larvae frass. Maximum Academic Press; 2023.
- [13] Saputra I, et al. Nutritional composition of commercial full-fat and defatted black soldier fly larvae meal as a potential protein resource for aquafeeds. *Biodiversitas*. 2023;24(9):4877–4884.
- [14] Shumo M, et al. The nutritive value of black soldier fly larvae reared on common organic waste streams in Kenya. *Scientific Reports*. 2019;9(1).
- [15] Rampure SM, et al. Influence of fruit and vegetable waste substrates on the nutritional profile of black soldier fly (*Hermetia illucens*) larvae and prepupa. *International Journal of Tropical Insect Science*. 2025;45(1):433–445.
- [16] Tippayadara N, et al. Replacement of fish meal by black soldier fly (*Hermetia illucens*) larvae meal: effects on growth, haematology, and skin mucus immunity of Nile tilapia (*Oreochromis niloticus*). *Animals (Basel)*. 2021;11(1).
- [17] Vodounnou JV, et al. Complete substitution of fish meal with black soldier fly larvae meal at varying incorporation rates for feeding *Oreochromis niloticus* raised in captivity. *Aquaculture Science and Management*. 2025;2(1).
- [18] Henry M, et al. Use of black soldier fly (*Hermetia illucens*) larvae meal in aquafeeds for a sustainable aquaculture industry: a review. *Aquaculture*. 2022;553.
- [19] Nguyen NT. Black soldier fly larvae meal as a sustainable alternative to fishmeal in juvenile swamp eel diets: effects on growth and meat quality. *Aquaculture Journal (MDPI)*. 2025;5(1).
- [20] Herve MK, et al. Black soldier fly (*Hermetia illucens*) larvae improve growth performance and flesh quality of African catfish (*Clarias gariepinus*). *Discover Animals (Springer Nature)*. 2025;2.
- [21] Meneguz M, et al. Effect of rearing substrate on growth performance, waste reduction efficiency and chemical composition of black soldier fly larvae. *Journal of the Science of Food and Agriculture*. 2018;98(15):5776–5784.
- [22] Liu X, et al. Dynamic changes of nutrient composition throughout the entire life cycle of black soldier fly. *PLoS One*. 2017;12(8).
- [23] Purnamasari DK, et al. Black soldier fly larvae: cultivation and potential as an alternative protein source for poultry. *Livestock Research for Rural Development*. 2024;36(2).
- [24] Gatlin DM, et al. Evaluation of lauric acid enhancement of black soldier fly larvae from coconut. *Journal of Economic Entomology*. 2024;117(4):1235–1241.
- [25] Lalander CH, et al. Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly. *Journal of Cleaner Production*. 2018;172:911–919.

- [26] Mazza L, et al. Management of chicken manure using black soldier fly larvae assisted by companion bacteria. *Journal of Cleaner Production*. 2020;270.
- [27] Insect School. Black Soldier Fly (BSF) Farming. 12 January 2023.
- [28] Lu S, et al. Nutritional composition of black soldier fly larvae (*Hermetia illucens* L.) and its potential uses as alternative protein sources in animal diets: a review. *Insects*. 2022;13(9).
- [29] Liu Z, et al. Bioconversion of three organic wastes by black soldier fly (Diptera: Stratiomyidae) larvae. *Environmental Entomology*. 2018;47(6):1609–1617.
- [30] Meneguz M, et al. Bioprocessing of organic wastes from poultry and bovine slaughterhouses as food substrate for *Hermetia illucens* larval development. *Global Journal of Environmental Science and Management*. 2023;9(1):31–42.
- [31] Mohamad Zulkifli NFN, et al. Nutritional value of black soldier fly (*Hermetia illucens*) larvae processed by different methods. *PLOS ONE*. 2022;17(2).
- [32] Pham Thi Phuong Lan, et al. Amino acid and fatty acid compositions of black soldier fly larvae fed tofu by-products in Viet Nam. *Livestock Research for Rural Development*. 2022.
- [33] Radhakrishnan G, et al. Assessing amino acid solubility of black soldier fly larvae meal in Atlantic salmon in vivo and in vitro. *Frontiers in Physiology*. 2022;13.
- [34] Lemme A, Pieper K. Rethinking amino acid nutrition of black soldier fly larvae based on insights from an amino acid reduction trial. *Insects (MDPI)*. 2024;15(11).
- [35] Barragan-Fonseca KB, et al. Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed — a review. *Journal of Insects as Food and Feed*. 2017;3(2):105–120.
- [36] Spranghers T, et al. Nutritional composition of black soldier fly (*Hermetia illucens*) prepupae reared on different organic waste substrates. *Journal of the Science of Food and Agriculture*. 2017;97(8):2594–2600.
- [37] Truzzi C, et al. Fatty acids profile of black soldier fly (*Hermetia illucens*): influence of feeding substrate based on coffee-waste silverskin enriched with microalgae. *Animal Feed Science and Technology*. 2020;259.
- [38] Li X, et al. Growth and fatty acid composition of black soldier fly larvae are influenced by dietary fat sources and levels. *Animals*. 2022;12(4).
- [39] Surendra KC, et al. Rethinking organic wastes bioconversion: evaluating the potential of the black soldier fly. *Waste Management*. 2020;117:58–80.
- [40] Makkar HPS, et al. State-of-the-art on use of insects as animal feed. *Animal Feed Science and Technology*. 2014;197:1–33.
- [41] Newton GL, et al. Using the black soldier fly (*Hermetia illucens*) as a value-added tool for the management of swine manure. *ResearchGate*; 2005.
- [42] van Huis A. Potential of insects as food and feed in assuring food security. *Annual Review of Entomology*. 2013;58:563–583.
- [43] Allegretti G, et al. Insect as feed: an emergy assessment of insect meal as a sustainable protein source for the Brazilian poultry industry. *Journal of Cleaner Production*. 2018;171.
- [44] St-Hilaire S, et al. Fish offal recycling by the black soldier fly produces a foodstuff high in omega-3 fatty acids. *Journal of the World Aquaculture Society*. 2007;38(2):309–313.
- [45] Hoc B, et al. About lipid metabolism in *Hermetia illucens* (L. 1758): on the origin of fatty acids in prepupae. *Scientific Reports*. 2020;17 July.
- [46] Lakew A, Fantahun F. Replacement of fishmeal with black soldier fly (*Hermetia illucens* L.) larvae enhances growth performance of Nile tilapia (*Oreochromis niloticus* L.) fry in tanks. *Ethiopian Journal of Agricultural Sciences*. 2024;34(3).
- [47] Dogan HT, Turker F. The usage of black soldier fly (*Hermetia illucens*) larvae meal as alternative protein source in carp diets (*Cyprinus carpio*). *Acta Aquatica Turcica*. 2021;6(4):508–514.
- [48] Dogan HT, Turker F. [Duplicate of [47] — merged.] *Acta Aquatica Turcica*. 2021;6(4):508–514.
- [49] Chen Y, et al. Evaluation of dietary black soldier fly larvae meal on growth performance, intestinal health, and disease resistance to *Vibrio parahaemolyticus* of Pacific white shrimp (*Litopenaeus vannamei*). *Frontiers in Marine Science*. 2021;8.
- [50] Xie S. Replacing up to 20% of fishmeal with BSF meal improved intestinal microbiota and enhanced resistance to *Vibrio parahaemolyticus*. *Global Seafood Alliance*; 2021.
- [51] Weththasinghe P, et al. Full-fat black soldier fly larvae meal and paste in extruded diets for Atlantic salmon (*Salmo salar*): effect on physical pellet quality, nutrient digestibility, and growth performances. *Aquaculture*. 2020;530.
- [52] Manh HN, et al. Effect of inclusion of fresh or dried black soldier fly larvae in diets on snakehead fish's growth performance and chemical composition (*Channa* sp.). *Israeli Journal of Aquaculture — Bamidgeh*. 2024;76(1).
- [53] Aisyah HN, et al. The effect of feeding black soldier fly larvae on growth performance, protein, and fat content of red hybrid tilapia (*Oreochromis* spp.). *Veterinary World*. 2022;15(10):2453–2457.
- [54] Abdul Kari Z, et al. Effect of fish meal substitution with black soldier fly (*Hermetia illucens*) L. on growth performance, feed stability, blood biochemistry, and liver and gut morphology of Siamese fighting fish (*Betta splendens*). *Aquaculture Nutrition*. 2023.
- [55] Rawski M, et al. Black soldier fly full-fat larvae meal is more profitable than fish meal and fish oil in Siberian sturgeon farming: effects on aquaculture sustainability, economy, and fish GIT development. *Animals*. 2021;11(3).
- [56] Chu J-H, Huang T-W. Evaluation of black soldier fly larvae meal on growth, body composition, immune responses, and antioxidant capacity of redclaw crayfish (*Cherax quadricarinatus*) juveniles. *Animals (MDPI)*. 2024;14(3).

- [57] Naser El Deen S, et al. Bioconversion of different waste streams of animal and vegetal origin and manure by black soldier fly larvae (*Hermetia illucens* L.). *Insects*. 2023;14(2).
- [58] Li T, et al. Utilizing black soldier fly larvae to improve bioconversion and reduce pollution: a sustainable method for efficient treatment of mixed wastes of wet distiller grains and livestock manure. *Molecules*. 2023;28(15).
- [59] Lk DA. Hail the black soldier fly: turning waste into animal feed. 2023. [Industry report]
- [60] Ahmad IK, et al. Potential application of black soldier fly larva bins in treating food waste. *Insects (MDPI)*. 2023;14(5).
- [61] Liew CS, et al. Life cycle assessment: sustainability of biodiesel production from black soldier fly larvae feeding on thermally pre-treated sewage sludge under a tropical setting. *Waste Management*. 2023;164:238–249.
- [62] Mohan K, et al. Black soldier fly (*Hermetia illucens*) larvae as potential feedstock for biodiesel production: recent advances and challenges. *Science of the Total Environment*. 2023;859(Part 1).
- [63] Li Q, et al. Bioconversion of dairy manure by black soldier fly for biodiesel and sugar production. *Waste Management*. 2011;31(6):1316–1320.
- [64] Liew CS, et al. Fungal fermented palm kernel expeller as feed for black soldier fly larvae in producing protein and biodiesel. *Journal of Fungi*. 2022;8(4).
- [65] Bessa LW, et al. Food safety of consuming black soldier fly (*Hermetia illucens*) larvae: microbial, heavy metal and cross-reactive allergen risks. *Foods*. 2021;10(8).
- [66] Jackson L. Black soldier fly larvae meal producers get innovative, collaborative. *Responsible Seafood Advocate*; 2023.

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