Academic Education Publishing House

Research Progress on the Nutritional Metabolism, Regulatory Mechanisms, and Applications of Black Soldier Fly Oil

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Abstract: Black soldier fly (*Hermetia illucens*) larvae are increasingly studied as a resource insect because they grow quickly, utilize many organic residues, and generate biomass rich in protein and lipid. Among the products recovered from larvae, BSF oil is notable for its lauric-, palmitic-, oleic-, and linoleic-acid fractions, which are associated with oxidative resistance, nutritional value, and processing adaptability. This review summarizes the fatty acid features of BSF oil and discusses how substrate formulation, stocking density, temperature, moisture, developmental stage, and light exposure affect oil yield and lipid quality. The review then examines lipid deposition from physiological and molecular perspectives, focusing on fatty acid biosynthesis, lipid-reserve mobilization, and regulatory genes involved in lipid metabolism. Reported uses of BSF oil in feed, food processing, biodiesel, medical and health-related products, cosmetics, and daily chemical manufacturing are also evaluated. At present, wider industrial use is still restricted by heterogeneous substrates, insufficient quality specifications, limited safety evidence, and instability during processing. Future work should combine mechanistic studies with controlled rearing, oil refining and modification, and regulatory standardization, so that BSF oil can be used more reliably in high-value and large-scale applications.

Keywords: Black Soldier Fly; Oil; Metabolic Regulation; Animal Production and Food; Resource Utilization

1. Introduction

Population growth and food-security pressure have intensified interest in edible insects as alternative food and feed resources [1]. Insects and microorganisms that transform organic residues into proteins, lipids, and other nutrients provide a practical option for both food-supply relief and waste valorization. The black soldier fly (*Hermetia illucens* L., BSF), a dipteran insect in Stratiomyidae, can biotransform livestock and poultry manure, kitchen waste, distillers grains, animal viscera, straw, and other agricultural by-products into nutrient-dense biomass. Its body generally contains 35-60% protein, 20-40% crude fat, approximately 7% ash, nearly 4% neutral detergent fiber, and minor mineral elements such as Ca, P, K, and S [2,3] (figure 1). Bioactive constituents, including antimicrobial peptides, lauric acid, and chitin, are also present [3]. Because BSF larvae are nutrient-rich and digestible, their inclusion in animal diets can improve growth performance, strengthen disease resistance, and reduce feeding cost [3].

The lipid fraction of BSF biomass merits particular attention. It can be recovered at relatively high levels and has a fatty acid pattern that differs from many conventional lipid sources. BSF oil is rich in saturated fatty acids, especially lauric acid (C12:0) and palmitic acid (C16:0), a composition that contributes to its relatively good oxidative stability. It also contains nutritionally relevant unsaturated fatty acids, mainly oleic and linoleic acids; accordingly, its use is not limited to feed but may extend to food processing, oleochemical production, and bioenergy. This review therefore examines BSF oil composition, the main biological and rearing factors that shape yield and quality, mechanisms of lipid metabolism, and recent downstream applications, with the goal of supporting value-added utilization and industrial development. Unlike broader reviews that treat BSF larvae mainly as feed ingredients or general biomass resources, this review focuses specifically on BSF oil and connects its compositional attributes with rearing-dependent regulation, lipid-metabolic mechanisms, and application constraints. Particular attention is given to how production conditions determine oil quality and how mechanistic knowledge can support standardized, high-value utilization.

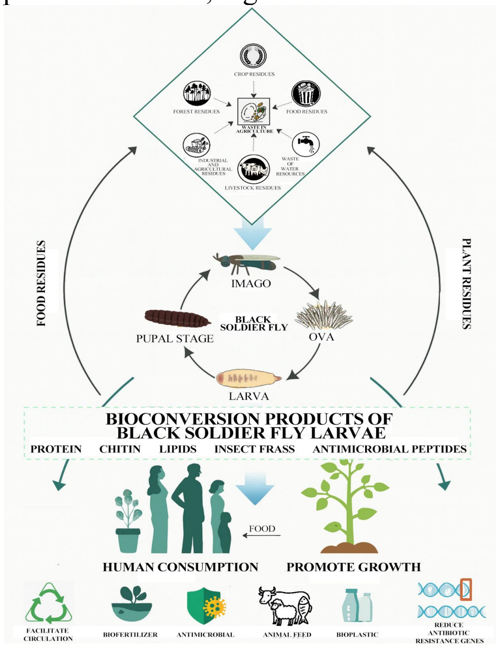

Figure 1. Life Cycle of *H. illucens* and Representative Products Derived from BSF Biomass

2. Compositional Characteristics of BSF Oil

BSF larvae contain a substantial lipid fraction. The oil recovered from larvae is dominated by saturated fatty acids, especially lauric acid (C12:0), myristic acid (C14:0), and palmitic acid (C16:0). Lauric and palmitic acids together represent more than 80% of total saturated fatty acids [4]. In addition, BSF oil contains oleic acid (C18:1), linoleic acid (C18:2), minor sterols, and small quantities of tocopherols and tocotrienols [5,6]. Its fatty acid composition changes across development rather than remaining constant: oleic acid and polyunsaturated fatty acids are more abundant in the larval stage, whereas lauric acid reaches its highest proportion during pupation [7].

Table 1 indicates that lauric acid accounts for 40.93% of total fatty acids in BSF oil, close to the proportion found in coconut oil. Compared with mustard seed oil and peanut oil, BSF oil has fewer unsaturated fatty acids but more medium-chain fatty acids, which may benefit digestion and metabolic utilization in animals. Lauric acid is also associated with antibacterial and antiviral effects, making it one of the components that separates BSF oil from many conventional edible oils [8]. These features support its use in antibiotic-free feed systems, cosmetic formulations, and medical-related products. Since commercial lauric acid is mainly obtained from coconut oil and palm kernel oil, BSF oil, with a comparable tropical-oil-like profile and a relatively higher linoleic acid content [9], could serve as another source of functional lipid ingredients.

Table 1. Fatty Acid Composition of Common Oils and Fats (% of Total Fatty Acids)

Fatty acid	Black soldier fly oil [10]	Mustard seed oil [11]	Peanut oil [11]	Palm oil [12]	Beef tallow [12]	Coconut oil [13]
Decanoic acid (C10:0)	0.67	0.04	-	0.03	0.07	6.11
Lauric acid (C12:0)	40.93	0.01	-	0.24	0.08	48.63
Myristic acid (C14:0)	6.49	0.06	0.09	0.88	2.95	18.36
Myristoleic acid (C14:1)	0.27	-	-	-	0.54	-
Pentadecanoic acid (C15:0)	0.06	0.02	-	0.04	0.53	-
Palmitic acid (C16:0)	19.11	2.83	10.50	39.07	26.17	8.67
Palmitoleic acid (C16:1)	3.89	0.13	0.08	0.14	1.66	-
Heptadecanoic acid (C17:0)	0.05	0.03	0.07	0.09	1.47	-
Stearic acid (C18:0)	1.73	1.31	3.59	4.31	25.70	3.61
Oleic acid (C18:1 n-9)	17.34	23.80	39.59	44.03	37.13	5.49
Linoleic acid (C18:2 n-6)	8.79	15.00	39.00	10.33	2.47	0.82
Linolenic acid (C18:3 n-3)	0.59	-	-	0.21	0.22	-
Arachidic acid (C20:0)	0.06	0.84	1.23	0.36	0.45	-
Unsaturated fatty acids	31.00	93.86	79.60	54.87	42.33	6.31
Saturated fatty acids	69.00	6.14	20.40	45.13	57.53	93.69

The fatty acid profile of BSF oil is readily influenced by diet. Marco et al. [14] added *Schizochytrium* by-products to the BSF diet and recorded significant increases in total larval fat and polyunsaturated fatty acids. Under standard rearing conditions, BSF oil generally contains no EPA/DHA, or only trace amounts [15]. Yet substrates supplemented with PUFA-rich materials, including algae, fish waste, and oilseed cakes such as flaxseed cake, show that BSF larvae can bioaccumulate PUFAs and generate a fatty acid profile more favorable for animal nutrition [16,17]. This dietary responsiveness provides a basis for producing BSF oil with targeted fatty acid characteristics.

Heat tolerance also depends on fatty acid composition. Oils rich in saturated and monounsaturated fatty acids usually resist heating better than PUFA-rich oils, which are more prone to oxidative degradation [18]. As

Table 2 shows, saturated fatty acids form the main fraction of BSF oil, helping explain its higher thermal stability than mealworm, cockroach, or cricket oils. Its medium-chain fatty acids, particularly lauric acid, may further improve digestibility and provide rapid energy in animal nutrition. By comparison, utilization of long-chain saturated fatty acids such as C16:0 and C18:0 is more strongly affected by chain length, lipid structure, and digestive conditions [19]. These compositional features give BSF oil advantages in digestion, nutrient utilization, and short-term energy supply.

Table 2. Fatty Acid Profiles of Selected Insect Oils (% of Total Fatty Acids)

Fatty acid class	Black soldier fly oil [20]	Maggot oil [21]	Mealworm oil [21]	Cricket oil [21]	Cockroach oil [22]	Red palm weevil oil [23]	Superworm oil [24]
C12:0	36.40	43.10	0.37	0.18	-	2.65	0.46
C14:0	6.89	15.30	3.13	0.86	-	2.21	1.87
C16:0	15.32	14.30	19.50	31.20	15.95	39.57	30.32
C18:0	1.40	2.39	4.43	9.03	6.02	1.68	8.77
ΣSFA	61.41	75.09	27.43	41.27	24.64	46.99	41.43
C16:1n-7	2.39	2.73	1.44	0.80	2.90	5.82	0.67
C18:1n-9	21.10	16.40	44.60	25.80	54.26	45.22	33.49
ΣMUFA	25.06	19.13	46.04	26.60	58.28	51.46	34.38
C18:2n-6	11.01	3.61	24.00	27.90	15.66	1.31	20.78
C18:3n-3	2.50	0.03	0.91	1.39	-	0.24	1.38
C20:4n-6	0.02	-	-	0.02	-	-	-
C20:5n-3	0.04	0.04	0.13	0.12	-	-	-
n-6 PUFA	11.03	3.61	24.00	27.92	16.05	-	-
n-3 PUFA	2.54	0.07	1.04	1.51	0.89	-	-
ΣPUFA	13.57	3.68	25.04	29.43	17.08	1.55	22.29

The total saturated fatty acid content of BSF oil is approximately 61.41%, lower than that of maggot oil (75.09%) but higher than that of red palm weevil oil (46.99%), mealworm oil (27.43%), and cricket oil (41.27%). This intermediate-to-high saturation contributes to oxidative stability without reaching the extreme saturation reported for some other insect oils. The unsaturated fraction mainly includes MUFAs, especially oleic acid (C18:1n-9), and PUFAs, particularly linoleic acid (C18:2n-6), which accounts for 11.03% [4]. These unsaturated fatty acids add nutritional value, although their biological effects still require verification under defined intake levels and application settings. Taken as a whole, BSF oil combines the functional value of medium-chain saturated fatty acids, the storage stability of saturated lipids, and the nutritional contribution of unsaturated fatty acids, supporting its use as a feed lipid, food additive, nutritional fortifier, or source of bioactive lipid compounds.

3. Factors Affecting the Yield and Quality of BSF Oil

3.1 Rearing Substrate

Rearing substrate affects BSF lipid deposition through nutrient supply and larval development. PUFA-rich diets can increase alpha-linolenic acid accumulation in larvae [25], whereas high-fat diets may raise the lauric acid content of BSF oil [26]. Wheat-bran-reared larvae have been reported to contain up to 54.24% lauric acid, and a wheat bran-olive pomace mixture further increased this value to 56.32-60.33% [27]. Gu et al. [28] found that supplementation of microalgae with *Bacillus subtilis*, yeast, and *Lactobacillus plantarum* improved larval bioconversion efficiency and increased amino acid and saturated fatty acid contents. Lu et al. [29] similarly supplemented kitchen waste with *Bacillus subtilis* strain NJZ, *Bacillus licheniformis* strain NY, *Lactobacillus plantarum* strain RS72, and *Enterococcus faecalis* strain L102, resulting in better lipid conversion. After microbial addition, larval oil yield rose from 10.4% in the control to 12.8-14.4%. Mazza et al. [30] also reported that combining BSF larvae with associated bacteria in chicken manure treatment promoted larval growth, increased fat content, and reduced residual manure. These observations suggest that introduced microorganisms may act together with the native gut microbiota of BSF larvae to enhance lipid deposition.

Substrate type and macronutrient balance are equally important. Abdolreza [31] compared kitchen waste, tofu by-products, and vegetable residues and found the highest bioconversion and fat conversion rates in larvae fed tofu by-products. In another study, milkfish offal produced the highest larval survival rate (90.44%), whereas vegetable waste generated the highest larval fat content (40.55%) [32]. Larval crude fat accumulation is closely related to substrate lipid, carbohydrate, protein, and fiber contents. Increasing protein and non-fiber carbohydrate supply, while avoiding excessive fat and cellulose, can improve conversion efficiency. Yan et al. [33] adjusted the C:N ratio of food waste with urea from 21:1 to 18:1, 16:1, 14:1, 12:1, and 10:1. Performance declined significantly at C:N ratios of 12:1-10:1, whereas ratios of 18:1-16:1 enhanced the bioconversion efficiency of larval protein and fat. Rehman et al. [34] reported optimal BSF conversion of chicken and dairy manure at a C:N ratio of 14.2:1 and pH 7.8. Carpentier et al. [35] cultured BSF larvae using mannuronic acid (MAL), sucrose (SUC), glutamate (GLU), fructose (FRU), galacturonic acid (GAL), and N-acetylgalactosamine (LAC), and lipid content exceeded 30% in all treatments.

Excess protein, however, is not necessarily beneficial for lipid deposition and may reduce the proportion of nutrients directed toward fat storage. High-energy feeds can increase growth rate and pupal weight, but they may also increase mortality; excessive energy intake may further weaken disease resistance. Physical characteristics of the substrate should also be considered. High viscosity restricts gas exchange between the substrate and air, reduces oxygen availability inside the material, delays larval development, and ultimately constrains lipid accumulation.

3.2 Stocking Density

Aggregation is pronounced in early BSF larvae [36]. Young larvae respond to chemical cues, feed collectively, and create a localized microenvironment that may accelerate growth. As larvae become older and more mobile, this aggregation gradually weakens. Guo [37] tested five density treatments, ranging from 50 to 250 larvae, in a medium with a total dry weight of 193.814 g. The 50-larvae treatment showed better individual growth than the higher-density treatments, suggesting that overcrowding intensifies competition for feed and space. Reduced access to feed can then lead to uneven growth and premature pupation. Production systems therefore need an upper density limit that balances output per unit area with population uniformity.

Li [36] observed the best growth performance at 0.96 larvae/cm^2, although material conversion efficiency remained relatively low. Raising density can increase larval output per unit area, but when density exceeds 1.92 larvae/cm^2, competition reduces feed availability for individual larvae, decreases mean body weight, increases developmental heterogeneity and disease risk, and prolongs the larval period. Previous work also showed that larval nutritional composition declines above 0.64 larvae/cm^3 [10]. These findings indicate that excessive crowding reduces effective nutrient supply, limits nutrient deposition, increases stress-related energy expenditure, and raises heat production per unit area, thereby disturbing feeding, growth, and lipid accumulation.

3.3 Temperature

Temperature is a central environmental factor in BSF larval growth and metabolism. It affects reproduction, survival, hatching, lifespan, feeding activity, and the balance between lipid synthesis and lipid catabolism. The optimal temperature for larval development is generally considered to be 27 ± 1°C [17]. At higher temperatures, larval metabolic rate increases and a larger share of dietary energy is used for maintenance and activity; this shift may stimulate fatty acid oxidation and reduce energy stored as lipid [17]. Under low-temperature conditions, feeding and respiratory activity decline, metabolic turnover is suppressed, and larval development can slow markedly.

Li [36] reported significantly higher dry matter utilization at 27°C than at 20°C or 34°C, indicating more efficient nutrient retention under the optimal thermal condition. Temperature also influences larval water balance. As temperature increases, evaporative water loss becomes greater, and larvae may compensate by consuming more feed [36]. Such compensation does not necessarily increase lipid deposition, because heat stress redirects energy toward survival and maintenance. In general, both heat and cold stress disrupt larval metabolism and reduce the efficiency of lipid accumulation.

3.4 Humidity

Moisture availability is another determinant of larval development and lipid deposition. Moderate moisture favors feeding, substrate utilization, and metabolic turnover, whereas overly dry or excessively wet conditions impair development and suppress lipid accumulation. Larvae reportedly stop developing at 40% substrate moisture, while those reared at 70% moisture grow faster and reach a larger body size than larvae reared at 55% moisture [38]. When moisture is too high, however, water fills substrate pores, oxygen diffusion declines, and larval survival may decrease.

Moisture can also reshape the fatty acid profile of BSF larvae [17]. Larvae synthesize saturated fatty acids from dietary carbohydrates, but this pathway may be inhibited under humid conditions, resulting in a relative increase in unsaturated fatty acids as part of the response to high moisture. Under dry conditions, water limitation may shift metabolism toward water-saving strategies. This response can shorten development and induce prepupation at a smaller body size. Because larvae commonly attain the greatest body weight in moist substrates [17], excessive dryness may limit both growth duration and final lipid accumulation.

3.5 Developmental Stage

BSF lipid deposition changes substantially with developmental stage. The life cycle includes egg, larval, prepupal, pupal, and adult stages [9]. Liu et al. [39] reported that eggs from larvae fed chicken feed contained 15.8% fat; the value fell to 4.8% on the first day after hatching, then increased during larval development and reached 28.0% before the prepupal stage. Fat content decreased sharply during pupation and later increased in adults, reaching 30.6% in females and 32.2% in males. Using LC-MS-based lipidomics, Li et al. [40] found that body weight and fat content increased during larval growth, whereas glycerophospholipids, sphingolipids, and derived lipids decreased relatively. Before prepupation, larvae preferentially store fat as the major energy reserve for the subsequent non-feeding metamorphic stages. The pupal stage involves strong lipid consumption and therefore reduces both lipid content and nutritional value. For this reason, larvae are usually harvested before pupation when the objective is to maximize BSF oil recovery.

3.6 Light Exposure

Light exposure affects both larval growth and the expression of lipid-metabolism-related genes. Larvae kept under darker conditions have significantly higher crude fat content than those exposed to light. Huang et al. [41] reported that crude fat in the illuminated group was 1.62% lower than in the dark group ($P < 0.05$). Zhao et al. [42] exposed 6-day-old larvae to several artificial light intensities and found that body length and body weight were optimal under a 1000 Lux tungsten iodide lamp, whereas high-intensity light at 2000 Lux inhibited growth.

The effect of light is not limited to direct physiological regulation; it also changes feeding behavior and the substrate microenvironment. In darkness, evaporation and heat loss from the substrate surface are reduced, moisture remains more stable, and larvae can feed for longer periods. Under illumination, larvae tend to avoid light and shorten feeding bouts. Repeated feeding interruption may lower basal metabolic rate and feeding-associated heat production, followed by compensatory feeding during later dark intervals; nevertheless, cumulative fat deposition may still be lower. Coordinated control of light and humidity may therefore help stabilize substrate moisture, regulate metabolism, and maintain high-turnover production with controlled lipid accumulation [41].

4. Regulatory Mechanisms of Lipid Metabolism in BSF

The BSF gut contains proteases, amylases, lipases, and other digestive enzymes that hydrolyze proteins, carbohydrates, and lipids in organic wastes, enabling efficient conversion of these nutrients into biomass [43]. Light conditions also affect enzymes involved in lipid metabolism. Reported data indicate that illumination can regulate lipid-metabolic enzyme expression. In larvae reared in darkness, mRNA levels of acetyl-CoA carboxylase (ACC), fatty acid synthase (FAS), lipase (LIP), acyl-CoA dehydrogenase (ACD), and other lipid-related genes were significantly higher than in light-exposed larvae, suggesting that darkness is favorable for larval growth and fat deposition [41].

Transcriptomic and genomic studies have identified ACC and FAS as key rate-limiting enzymes in BSF lipid metabolism [44,45]. In insects, these enzymes participate in lipid storage, cuticular lipid synthesis, and stress tolerance. Mai et al. [46] found that ACC expression increased during larval development, peaked on day 9, and then declined in the pupal stage. Higher ACC and FAS expression in early larvae supports lauric acid synthesis and energy storage, whereas lower ACD and LIP expression during the prepupal stage suggests that nutrients accumulated during feeding are sufficient to support subsequent development [47]. Stage-specific expression of LIP and ACD in larvae and prepupae may assist the mobilization of lipid reserves required by non-feeding stages.

Work on BSF lipid metabolism has begun to link whole-organism phenotypes with molecular regulation. Zhu et al. [44] showed that most upstream processes preceding fatty acid biosynthesis occur in the early stage, whereas rapid fat deposition is concentrated later. Hoc et al. [17] used two diet formulations, chicken feed and 40% chicken feed mixed with 60% flaxseed cake, moistened with ordinary water (H_2O) or deuterium oxide (D_2O), to trace newly synthesized fatty acids. Dietary carbohydrate level was shown to be a central factor in BSF fatty acid synthesis. Evidence from Zhu's transcriptomic results and Hoc's ^2H_2O tracing indicates that carbohydrates are converted through the glycolysis-pyruvate-acetyl-CoA-fatty acid-TAG pathway. Days 1-4 of larval development and the late prepupal stage appear to be important windows of rapid lipid deposition, during which crude fat increased from 7.5% to 26.1% and lauric acid reached 75.5%. After prepupation, feeding stops while energy use continues, so lipid levels decline. These results identify ACC and FAS as useful targets for explaining BSF lipid biosynthesis and improving lipid accumulation in large-scale production.

Several FAS genes, including HiFAS1, HiFAS2, and HiFAS3, have been identified in the BSF genome. They are highly expressed in larvae and fat bodies, but their expression decreases during starvation or under high-fat dietary conditions. In insects, absorbed nutrients are stored mainly as triacylglycerols, while fatty acids also function in membrane construction, cellular signaling, and metabolic homeostasis [48]. Acyltransferases and desaturases further contribute to directional conversion of exogenous fatty acids. BSF larvae can efficiently convert substrate-derived trans-fatty acids and medium-chain fatty acids into lauric acid and oleic acid, two fatty acids that are abundant in their endogenous lipid profile [49].

Adipokinetic hormone (AKH) and its receptor (AKHR) may also participate in BSF lipid accumulation. AKH signaling acts through AKHR, and both components jointly regulate lipid metabolism in insects. Suppression of AKHR expression can increase lipid storage [50]. Future studies of BSF lipid regulation should therefore move beyond reported genes such as ACC and FAS and examine candidate transcription factors and regulatory networks that control fatty acid synthesis, oxidation, and reserve mobilization.

Taken together, lipid accumulation in BSF larvae can be interpreted as a linked metabolic sequence: substrate carbohydrates and lipids first determine acetyl-CoA availability through glycolysis and related pathways; ACC and FAS then drive de novo fatty acid synthesis, particularly medium-chain fatty acid formation; newly synthesized fatty acids are esterified into triacylglycerols and stored in the fat body; and LIP, ACD, AKH/AKHR signaling, and related regulatory networks mobilize these reserves during prepupal and pupal development [17,44,46,48-50]. This framework explains why substrate composition, developmental stage, temperature, and light exposure jointly alter BSF oil yield and fatty acid composition, and it also identifies metabolic nodes that may be targeted in controlled production.

5. Application Advances of BSF Oil

5.1 Application in Animal Production

As fishmeal and fish oil prices rise, BSF oil has attracted attention as an alternative feed lipid. Studies have reported partial replacement of conventional oils in poultry, livestock, and aquaculture diets. Kim et al. [51] found that broiler diets containing BSF oil increased lauric acid and essential fatty acids, including linoleic and linolenic acids, in muscle, while improving feed conversion ratio and serum antioxidant capacity. Dabbou et al. [52] showed that replacing part of soybean oil with modified BSF oil in broiler diets beneficially modulated gut microbiota without impairing growth performance, intestinal morphology, or tissue health. Nekrasov et al. [53] reported that dietary BSF oil supplementation in dairy cows did not adversely affect digestion; daily supplementation at 10 g per head increased average milk yield and improved milk fatty acid composition.

In aquaculture, Shi et al. [54] replaced soybean oil with BSF larvae oil in blood parrot cichlid diets and found that a 75% replacement level, equivalent to 6% larval oil in the diet, produced the best weight gain, body-color saturation, and serum biochemical indices. Xu et al. [55] replaced 50-100% of soybean oil with BSF larvae oil in juvenile mirror carp diets and significantly improved growth rate, feed conversion efficiency, and intestinal morphology. BSF oil may also be useful in pet food. Jian et al. [56] evaluated BSF larvae as protein or fat sources in beagle dogs and found that 8% BSF oil had no adverse effects on body condition, apparent nutrient digestibility, fecal microbiota, or metabolism. Compared with conventional pet food, dog food containing BSF protein and oil had a wider range of aroma compounds, better palatability, higher relative acid content, lower relative alkane and aldehyde contents, and a more favorable profile for pet health and growth [57].

5.2 Application in Biodiesel

BSF oil has also been explored as a feedstock for biodiesel. Biodiesel is renewable, biodegradable, and generally associated with lower pollutant emissions [58]. Because BSF oil is a non-food lipid source, its use may reduce competition with human food resources and ease pressure on first-generation biodiesel systems that rely mainly on edible oils [59]. Larval crude fat can be converted to biodiesel through esterification, and performance tests have shown that the resulting fuel properties meet the international biodiesel standard EN14214 [60]. One study further reported the highest engine performance with a blend containing 6.43% larval oil and 93.57% diesel [61].

Rehman et al. [60] tested diesel blended with BSF biodiesel and found that low-level incorporation, especially 10%, reduced nitrogen oxide emissions by 50% while maintaining fuel consumption close to that of conventional diesel. These results indicate that BSF oil is a possible cleaner bioenergy feedstock, although production cost, fuel stability, and supply-chain feasibility require further assessment before large-scale use.

5.3 Application in Food Production and Processing

BSF larvae oil has shown encouraging safety and functional properties for food-related applications. No pathogenic bacteria were detected after 55 weeks of storage, indicating good microbiological stability under the tested conditions [10]. Because BSF larvae oil can inhibit or delay selected foodborne and spoilage microorganisms, it may act as a fat substitute with preservative potential, especially in refrigerated and high-moisture foods that spoil rapidly. This function could reduce reliance on synthetic preservatives in products with short shelf lives [10]. Experimental data have confirmed antibacterial activity against Gram-positive bacteria and yeasts. Its unsaturated fatty acids and other bioactive lipid components also support possible use as a food ingredient or supplementary cooking oil [62].

Interest in BSF-derived ingredients for food products has increased. Delicato et al. [63] evaluated consumer responses to low-fat bakery products in which BSF larval fat partly replaced butter. Partial replacement did not lower product quality: 25% substitution had no adverse effect on texture, color, or overall preference, and 50% substitution remained acceptable in waffles. In some formulations, 25% inclusion even improved perceived flavor and produced favorable sensory attributes. Heating, however, may strengthen undesirable odor notes in BSF oil, especially fishy and greasy flavors. Refining and antioxidant addition may therefore be needed to improve flavor stability during cooking [19]. Oil color after heating is also important because it reflects chemical changes during processing and storage and directly affects consumer acceptance. Chang et al. [19] reported a significant decline in the color index of BSF oil at 180 °C, showing that further refining is needed for high-temperature or repeated-heating conditions. Current European policies already support BSF use in protein products, protein bars, and related food applications. Even so, consumer hesitation toward insect-derived ingredients remains a major barrier. Incorporating these components into familiar foods in less visible forms may reduce psychological resistance and improve acceptance [64].

5.4 Application in Medical and Health Fields

BSF oil is also relevant to medical and health-related applications. Excessive or inappropriate antibiotic use has accelerated bacterial resistance and increased the difficulty of clinical treatment. Because BSF oil contains antimicrobial fatty acids, particularly lauric and palmitic acids, it may serve as a natural lipid resource for antimicrobial applications. Lauric acid has antiviral, antibacterial, and antiprotozoal activities; it can disrupt bacterial membrane stability and inhibit bacterial energy metabolism, eventually leading to cell death [65]. This feature supports its possible use as an alternative antimicrobial strategy or functional lipid resource. Palmitic acid also shows antimicrobial activity against some harmful microorganisms [10]. Feeding juvenile mirror carp with 12.5-25 g/kg BSF larvae oil significantly decreased TNF-α and IL-1β expression in kidney and hepatopancreas tissues compared with diets containing 0-6.25 g/kg oil [55]. BSF larvae oil also significantly upregulated interleukin-10 (IL-10), which encodes the anti-inflammatory cytokine IL-10, in juvenile mirror carp [55,66], suggesting anti-inflammatory potential.

5.5 Application in Daily Chemical Products

As a renewable bio-based resource, BSF oil contains abundant fatty acids and fatty alcohols, which provide natural emollient and moisturizing components. It can be used in cosmetics, lubricants, surfactants, and other oleochemical products. Its biodegradability and low toxicity further strengthen its value in environmentally oriented product development. Through esterification, hydrogenation, and related conversion processes, BSF oil can be transformed into high-performance chemical raw materials, supporting sustainable chemical production. For skincare applications, Song [2] performed a comprehensive lipid analysis of BSF oil and identified functional lipid components such as ceramides and lecithin; DPPH assays also suggested a degree of antioxidant activity.

In composition, BSF oil resembles mealworm oil and maggot oil in several respects [67]. Maggot oil has been reported to be mild, non-irritating to damaged and normal skin, and unlikely to trigger allergic reactions when applied topically. By analogy, the relatively high linoleic acid content of BSF oil may help reduce water loss from open burn wounds and protect skin from dryness-related injury. Lauric acid provides antibacterial and preservative effects, which may limit oxidation and spoilage in creams and ointments. Its derivatives can also act as surfactants and assist removal of dirt and residues from skin and hair [9].

Outside cosmetics and dermatological products, BSF oil derivatives can form protective lubricating films and improve tribological performance [68]. BSF larvae oil has high viscosity, a high flash point, low volatility, and favorable lubricity. Chemical modification can further improve the stability of BSF-derived biolubricants. Such products may reduce production cost and lessen the environmental burden associated with conventional mineral lubricants. Enzymatic glycerolysis also allows selective conversion of larval oil into high-purity monoacylglycerols, providing another route for value-added use of BSF oil [69].

6. Conclusions and Prospects

BSF is a resource-efficient insect with clear value for organic waste bioconversion and biomass production. Its oil contains medium- and short-chain fatty acids, especially lauric acid, together with long-chain unsaturated fatty acids, giving it a distinctive lipid profile. Compared with many conventional edible oils, BSF oil can be produced through waste-based rearing systems and may be applied in animal nutrition, food processing, biodiesel, medical-related products, cosmetics, and oleochemical manufacturing. It therefore provides a possible link between organic waste treatment and sustainable lipid production.

Several barriers still limit industrial application of BSF oil, including unstable substrate composition, complex by-product management, variation in product quality among production systems, and insufficiently standardized regulation. These issues restrict commercialization and market acceptance. Future studies should clarify lipid metabolism at physiological, biochemical, and molecular levels; improve rearing, extraction, refining, and modification processes; and lower production cost while increasing product stability. Refining, deodorization, microencapsulation, and enzymatic modification may help address color and odor defects. For functional lipid development, oxidative stability remains a key bottleneck and should be improved through processing control and formulation design. Regulatory work is also needed: internationally harmonized standards should define approved substrates, safety limits, rearing conditions, oil-quality indicators, and application boundaries. Clear standards would reduce uncertainty in production and application and support broader commercialization of BSF-derived bioproducts.

References

[1] Lange K W, & Nakamura Y. Edible insects as future food: chances and challenges. Journal of Future Foods, 2021, 1(1): 38-46.
[2] Song X X. Component analysis of black soldier fly and preparation of its lipid microemulsion system. Wuhan Institute of Technology, 2024. (in Chinese)
[3] Wang L, Xu Z P, Wu D D, et al. Nutritional value of black soldier fly and its application in animal production. Feed Research, 2024, 47(23): 173-178. (in Chinese)
[4] Huang X, Xu Q X, Wu L, et al. Research progress on the feeding value of black soldier fly oil and its application in feed. Feed Research, 2024, 47(07): 157-162. (in Chinese)
[5] Ramos-Bueno R P, González-Fernández M J, Sánchez-Muros-Lozano M J, et al. Fatty

acid profiles and cholesterol content of seven insect species assessed by several extraction systems. European Food Research and Technology, 2016, 242(9): 1471-1477.

[6] Bertrand M, Thomas P, Heinrich K, et al. Renewable Resources from Insects: Exploitation, Properties, and Refining of Fat Obtained by Cold-Pressing from *Hermetia illucens* (Black Soldier Fly) Larvae. European Journal of Lipid Science and Technology, 2019, 121(7): 1800376.

[7] Cui J, Yang Z, Wang W, et al. Lipidomics approach reveals the dynamic changes in lipid profiles of black soldier fly (*Hermetia illucens*) during different growth stages. Food Science of Animal Products, 2024, 2(1): 9240049.

[8] Kierończyk B, Rawski M, Józefiak A, et al. Effects of replacing soybean oil with selected insect fats on broilers. Animal Feed Science and Technology, 2018, 240: 170-183.

[9] Yuan H L, Li X C, Sun Q X, et al. Research and comprehensive utilization of black soldier fly oil. Journal of Environmental Entomology, 2023, 45(5): 1174-1182. (in Chinese)

[10] Zabulionė A, Aalaševičienė A, Makštutienė N, et al. Exploring the Antimicrobial Potential and Stability of Black Soldier Fly (*Hermetia illucens*) Larvae Fat for Enhanced Food Shelf-Life. Gels, 2023, 9(10): 793.

[11] Zhang W C, Li H Z, Zhang Z J, et al. Comparison of fatty acid composition and antioxidant activity of eight different vegetable oils. China Oils and Fats, 2021, 46(04): 68-71. (in Chinese)

[12] Zhang C, Lu W J, Chen D, et al. Physicochemical properties, fatty acid composition and flavor of enzymatic-thermal oxidation compound beef tallow. Journal of Chinese Institute of Food Science and Technology, 1-14. (in Chinese)

[13] Cui Y Y. Effects of different oil preparation methods on main nutritional components, oil properties and protein properties of coconut. Hainan University, 2020. (in Chinese)

[14] El-Dakar, Marco A, et al. Bioaccumulation of residual omega-3 fatty acids from industrial *Schizochytrium* microalgal waste using black soldier fly (*Hermetia illucens*) larvae. Journal of Cleaner Production, 2020, 268: 122288.

[15] Ewald N, Vidakovic A, Langeland M, et al. Fatty acid composition of black soldier fly larvae (*Hermetia illucens*) - Possibilities and limitations for modification through diet. Waste Management, 2020, 102: 40-47.

[16] Liland, Nina S, et al. Modulation of nutrient composition of black soldier fly (*Hermetia illucens*) larvae by feeding seaweed-enriched media. PLoS One, 2017, 12(8): e183188.

[17] Hoc, Bertrand, et al. About lipid metabolism in *Hermetia illucens* (L. 1758): on the origin of fatty acids in prepupae. Scientific Reports, 2020, 10(1): 11916.

[18] Chang K A, Leong S Y, Chew L Y, et al. Physicochemical and Perceived Olfactory Changes in Black Soldier Fly (*Hermetia illucens*) Larvae Oil Under Domestic Cooking Temperatures. Foods, 2025, 14(13): 2333.

[19] Bogevik A S, Seppänen-Laakso T, Samuelsen T A, et al. Fractionation of Oil from Black Soldier Fly Larvae (*Hermetia illucens*). European Journal of Lipid Science and Technology, 2022, 124(5): 2100252.

[20] Rabani V, Cheatsazan H, & Davani S. Proteomics and Lipidomics of Black Soldier Fly (Diptera: Stratiomyidae) and Blow Fly (Diptera: Calliphoridae) Larvae. Journal of Insect Science, 2019, 19(3): 29.

[21] Anuraga J, Rinda G, Roni R, et al. Fatty acid profiles of some insect oils and their effects on bovine rumen fermentation and methanogenesis. Italian Journal of Animal Science, 2020, 19(1): 1310-1317.

[22] Perez-Santaescolastica C, de Pril I, van de Voorde I, et al. Fatty Acid and Amino Acid Profiles of Seven Edible Insects: Focus on Lipid Class Composition and Protein Conversion Factors. Foods, 2023, 12(22): 4090.

[23] Chen M, Kan J, Zhang Y, et al. Combined Analysis of Metabolomics and Biochemical Changes Reveals the Nutritional and Functional Characteristics of Red Palm Weevil *Rhynchophus ferrugineus* (Coleoptera: Curculionidae) Larvae at Different Developmental Stages. Insects, 2024, 15(4): 294.

[24] Mattioli S, Fratini F, Cacchiarelli C, et al. Chemical composition, fatty acid profile,

antioxidant content, and microbiological loads of lesser mealworm, mealworm, and superworm larvae. Italian Journal of Animal Science, 2024, 23(1): 125-137.
[25] Xia M, Hu Z, Wang G, et al. Evaluation of black soldier fly (*Hermetia illucens*) larvae oil as a potential lipid source for largemouth bass (*Micropterus salmoides*): Growth performance, myofiber development and glucolipid metabolism. Animal Feed Science and Technology, 2024, 318: 116102.
[26] Oonincx, Dennis GAB, et al. Correction: Feed Conversion, Survival and Development, and Composition of Four Insect Species on Diets Composed of Food By-Products. PLoS One, 2019, 14(10): e222043.
[27] Ramzy R R, El Dakar M A, Wang D, et al. Conversion Efficiency of Lignin-Rich Olive Pomace to Produce Nutrient-Rich Insect Biomass by Black Soldier Fly Larvae, *Hermetia illucens*. Waste and Biomass Valorization, 2022, 13(2): 893-903.
[28] Gu P, Chen L, Yang K, et al. Improving the conversion efficiency of cyanobacterial biomass and the value of black soldier fly products by inoculating microorganisms. Journal of Cleaner Production, 2024, 464: 142754.
[29] Lu Y, Zhang M Q, Yang X J, et al. Effects of calcium-containing minerals and microorganisms on lipid conversion efficiency during black soldier fly treatment of kitchen waste. Acta Scientiae Circumstantiae, 2021, 41(12): 4973-4985. (in Chinese)
[30] Mazza L, Xiao X, Rehman K U, et al. Management of chicken manure using black soldier fly (Diptera: Stratiomyidae) larvae assisted by companion bacteria. Waste Management, 2020, 102: 312-318.
[31] Hosseindoust A, Ha S H, Mun J Y, et al. Quality Characteristics of Black Soldier Flies Produced by Different Substrates. Insects, 2023, 14(6): 500.
[32] Pamintuan K R S, Cajayon J A B, Dableo G B. Growth Characteristics and Lipid Content of Black Soldier Fly (*Hermetia illucens*) Larva Reared in Milkfish Offal and Mixed Vegetable Wastes. In Proceedings of the 2019 6th International Conference on Biomedical and Bioinformatics Engineering (pp. 163-168).
[33] Yan L, Shouyu Z, Shibo S, et al. Effects of Different Nitrogen Sources and Ratios to Carbon on Larval Development and Bioconversion Efficiency in Food Waste Treatment by Black Soldier Fly Larvae (*Hermetia illucens*). Insects, 2021, 12(6): 507.
[34] Rehman K U, Cai M, Xiao X, et al. Cellulose decomposition and larval biomass production from the co-digestion of dairy manure and chicken manure by mini-livestock (*Hermetia illucens* L.). Journal of Environmental Management, 2017, 196: 458-465.
[35] Carpentier J, Martin C, Luttenschlager H, et al. Common soluble carbohydrates affect the growth, survival, and fatty acid profile of black soldier fly larvae *Hermetia illucens* (Stratiomyidae). Scientific Reports, 2024, 14(1): 28157.
[36] Li X. Optimization of growth conditions of black soldier fly and efficiency of kitchen waste treatment. Harbin Institute of Technology, 2021. (in Chinese)
[37] Guo X J. Optimization and application of nutritional formula for black soldier fly larvae. Nanchang University, 2016. (in Chinese)
[38] Seyedalmoosavi M M, Mielenz M, Veldkamp T, et al. Growth efficiency, intestinal biology, and nutrient utilization and requirements of black soldier fly (*Hermetia illucens*) larvae compared to monogastric livestock species: a review. Journal of Animal Science and Biotechnology, 2022, 13(1): 31.
[39] Xiu L, Xuan C, Hui W, et al. Dynamic changes of nutrient composition throughout the entire life cycle of black soldier fly. PLoS One, 2017, 12(8): e182601.
[40] Li M, Wang G, Shang R, et al. Comparative Lipid Profile Analysis of *Hermetia illucens* Larvae Fed Food Waste at Different Days of Age Using an LC-MS-Based Lipidomics Approach. Journal of Insect Science, 2021, 21(5): 17.
[41] Huang Z Z, Ye B P, Zeng X Y, et al. Effects of light and darkness on growth performance, crude protein, crude fat and lipid metabolism-related genes of black soldier fly larvae. Feed Industry, 2022, 43(15): 35-39. (in Chinese)
[42] Zhao J J, Luo Q, Jiang M F. Preliminary study on the effects of light factors on the

growth and development of black soldier fly larvae. Livestock and Poultry Industry, 2018, 29(12): 7-10. (in Chinese)

[43] Siddiqui S A, Ristow B, Rahayu T, et al. Black soldier fly larvae (BSFL) and their affinity for organic waste processing. Waste Management, 2022, 140: 1-13.

[44] Zhu, Zhaolu, et al. De novo transcriptome sequencing and analysis revealed the molecular basis of rapid fat accumulation by black soldier fly (*Hermetia illucens*, L.) for development of insectival biodiesel. Biotechnology for Biofuels, 2019, 12(1): 194.

[45] Alabaster A, Isoe J, Zhou G, et al. Deficiencies in acetyl-CoA carboxylase and fatty acid synthase 1 differentially affect eggshell formation and blood meal digestion in *Aedes aegypti*. Insect Biochemistry and Molecular Biology, 2011, 41(12): 946-955.

[46] Mai W H, Wang Z Y, Liu C, et al. Effects of sugar sources on growth and development, fat deposition, fatty acid profile and expression of glycolipid metabolism-related genes in black soldier fly larvae. Journal of Environmental Entomology, 1-16. (in Chinese)

[47] Giannetto A, Oliva S, Lanes C F C, et al. *Hermetia illucens* (Diptera: Stratiomydae) larvae and prepupae: Biomass production, fatty acid profile and expression of key genes involved in lipid metabolism. Journal of Biotechnology, 2020, 307: 44-54.

[48] Zhu L J, Yan T T, Dong M Y, et al. Cloning and expression pattern analysis of HiACC and HiFAS in *Hermetia illucens*. Chemistry & Bioengineering, 2023, 40(11): 20-27. (in Chinese)

[49] Zhang Z Y, Zhou J F, Wang J Q, et al. Processing and transformation of lipid resources by black soldier fly larvae. Chemistry & Bioengineering, 2024, 41(10): 33-38. (in Chinese)

[50] Wang Y. Preliminary study on the role of lipid metabolism-related genes in lipid mobilization of *Spodoptera litura* under starvation stress. Yangtze University, 2021. (in Chinese)

[51] Kim Y B, Kim D H, Jeong S B, et al. Black soldier fly larvae oil as an alternative fat source in broiler nutrition. Poultry Science, 2020, 99(6): 3133-3143.

[52] Dabbou, Sihem, et al. Modified Black Soldier Fly Larva Fat in Broiler Diet: Effects on Performance, Carcass Traits, Blood Parameters, Histomorphological Features and Gut Microbiota. Animals, 2021, 11(6): 1837.

[53] Nekrasov, Roman V, et al. Effect of Black Soldier Fly (*Hermetia illucens* L.) Fat on Health and Productivity Performance of Dairy Cows. Animals, 2022, 12(16): 2118.

[54] Shi H Y, Sun X L, Fang Z Z, et al. Effects of replacing soybean oil with black soldier fly larvae oil on growth, body color and serum physiological and biochemical indices of blood parrot cichlid. Feed Research, 2020, 43(01): 22-27. (in Chinese)

[55] Xu, Xinxin, et al. Effects of black soldier fly oil rich in n-3 HUFA on growth performance, metabolism and health response of juvenile mirror carp (*Cyprinus carpio var. specularis*). Aquaculture, 533, 2021: 736144.

[56] Jian, S., et al. Effects of black soldier fly larvae as protein or fat sources on apparent nutrient digestibility, fecal microbiota, and metabolic profiles in beagle dogs. Frontiers in Microbiology, 2022, 13: 1044986.

[57] Zhang L M, Yang K, Xin Z Q, et al. Effects of black soldier fly protein powder and oil on dog food palatability and analysis of main aroma substances. Feed Research, 2022, 45(08): 127-133. (in Chinese)

[58] Fonseca J M, Teleken J G, de Cinque Almeida V, et al. Biodiesel from waste frying oils: Methods of production and purification. Energy Conversion and Management, 2019, 184: 205-218.

[59] Fozy B, Sohrab H M, Idayu A M. Recent Trends, Potentials, and Challenges of Biodiesel Production from Discarded Animal Fats: a Comprehensive Review. BioEnergy Research, 2022, 16(2): 778-800.

[60] Rehman K U, Liu X, Wang H, et al. Effects of black soldier fly biodiesel blended with diesel fuel on combustion, performance and emission characteristics of diesel engine. Energy Conversion and Management, 2018, 173: 489-498.

[61] Kamarulzaman M K, Abdullah A. Multi-objective optimization of diesel engine performances and exhaust emissions characteristics of *Hermetia illucens* larvae oil-diesel fuel blends using response surface methodology. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2025, 47(1): 2952-2965.

[62] Wang Y, Shelomi M. Review of Black Soldier Fly (*Hermetia illucens*) as Animal Feed and Human Food. Foods, 2017, 6(10): 91.
[63] Delicato C, Schouteten J J, Dewettinck K, et al. Consumers' perception of bakery products with insect fat as partial butter replacement. Food Quality and Preference, 2020, 79: 103755.
[64] La Barbera F, Verneau F, Amato M, et al. Understanding Westerners' disgust for the eating of insects: The role of food neophobia and implicit associations. Food Quality and Preference, 2018, 64: 120-125.
[65] Luca B, Lorena V, Ludovico D, et al. Insect Derived Lauric Acid as Promising Alternative Strategy to Antibiotics in the Antimicrobial Resistance Scenario. Frontiers in Microbiology, 2021, 12: 620798.
[66] Xu X, Ji H, Belghit I, et al. Black soldier fly larvae as a better lipid source than yellow mealworm or silkworm oils for juvenile mirror carp (*Cyprinus carpio var. specularis*). Aquaculture, 2020, 527: 735453.
[67] Xiong H. Research on extraction, separation and recovery processes of lipids from black soldier fly oil. Wuhan Institute of Technology, 2019. (in Chinese)
[68] Wu H, Feng S J, Hu W J, et al. Performance of fifth-instar black soldier fly oil derivatives as lubricant additives. Tribology, 2024, 44(1): 87-96. (in Chinese)
[69] Xu W, Xu L, Liu X, et al. An Effective Strategy for the Production of Lauric Acid-Enriched Monoacylglycerol via Enzymatic Glycerolysis from Black Soldier Fly (*Hermetia illucens*) Larvae (BSFL) oil. Applied Biochemistry and Biotechnology, 2021, 193(9): 2781-2792.