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Review Article

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Biotechnological applications of *Hermetia illucens* in veterinary uses

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Abstract

Black soldier fly (BSF) larvae have emerged as a sustainable biotechnological resource for animal nutrition, veterinary medicine, and waste management. Rich in protein, essential amino acids, and bioactive compounds, black soldier fly (BSF) larvae are suitable for various animal species, promoting growth, immunity, and gut health. They are valuable not only for nutrition but also in veterinary fields, including wound debridement and as probiotic-rich soil amendments, thereby contributing to integrated agricultural systems. BSF's ability to transform organic waste into high-quality animal feed and organic fertilizer aligns with circular bioeconomy principles and addresses challenges in protein supply and environmental sustainability. Nevertheless, the industry faces hurdles in standardizing nutritional composition and maintaining cost competitiveness. Safety measures are crucial, requiring the use of contaminant-free substrates and proper processing to mitigate allergenicity and microbiological risks for commercial viability. Future research directions include optimizing rearing substrates for tailored nutritional profiles, conducting large-scale clinical trials for veterinary use, understanding the mechanisms of BSF bioactive compounds, and exploring the nutraceutical potential of isolated BSF oil and chitin, alongside long-term health and lifecycle assessments to foster the sustainable growth of BSF-based industries.

Keywords: Antimicrobial peptides; Bioeconomy; Chitin; Larvae; Nutraceuticals

1. Introduction

The global demand for animal protein was escalating rapidly, driven by population growth, urbanization, and rising income, particularly in developing regions. By 2050, the world's population was projected to surpass 10 billion, with animal protein consumption especially pork and poultry expected to double compared to current levels, creating unprecedented pressure on feed resources and production systems [1-3]. Traditional protein sources such as soybean meal and fishmeal, which were the mainstays of animal feed, faced significant challenges. These included high and volatile costs, limited supply, and substantial environmental impacts such as deforestation, overfishing, and greenhouse gas emissions. Moreover, the cultivation of soybeans and the harvesting of fishmeal compete directly with human food chains and contribute to biodiversity loss, raising both environmental and ethical concerns [1-4]. In response to these challenges, insects emerged as a promising, natural, and sustainable alternative for animal feed. Insects were highly efficient at converting organic waste into nutrient-rich biomass, required minimal land and water, and produced fewer greenhouse gases compared to conventional livestock. Among the various insect species, the black soldier fly (BSF, *Hermetia illucens*) stood out as a leading candidate due to its remarkable biological traits. BSF larvae (BSFL) could be reared on a wide range of organic substrates, including agricultural byproducts and food waste, and were capable of rapid growth and high feed conversion efficiency. Their bioconversion capabilities helped manage organic waste and yielded high-quality protein (32–53%) and fat, along with essential amino acids, minerals, and bioactive compounds. These attributes made BSFL a valuable and sustainable feed ingredient for animal production systems [1-2, 4-5]. This review focused on the application of BSF larvae, prepupae, oil, frass (excrement), and their derivatives in the diets of production animals (poultry, swine, aquaculture) and companion animals (pets). The objective was to comprehensively assess the nutritional value, functional benefits, safety aspects, and regulatory landscape associated with BSF-based feed ingredients. By synthesizing current research, this article aimed to inform stakeholders about the potential and limitations of integrating BSF-derived products into animal nutrition, ultimately contributing to more sustainable, efficient, and ethical food production systems.

2. Biology and production of black soldier fly Larvae (BSFL)

2.1. Lifecycle and key characteristics

The black soldier fly (BSF, *Hermetia illucens*) is increasingly recognized for its unique biological and production characteristics that make it a promising agent for sustainable waste management and the generation of high-value feed ingredients. Notably, BSF is a non-pest, non-vector species, meaning it does not transmit diseases to humans or animals, which is a critical advantage for large-scale rearing and feed applications [6, 7]. Its life cycle comprises egg, larval, prepupal, pupal, and adult stages, with the larval stage being the most voracious and responsible for the majority of organic waste bioconversion. BSF larvae can consume and convert a wide variety of organic wastes including food scraps, agricultural byproducts, and manure into protein- and lipid-rich biomass, achieving high bioconversion rates and significantly reducing waste volume in a short period (typically 12–20 days) [8-10]. The larvae's ability to thrive on diverse substrates and their efficient feed conversion ratio underpin their value in circular economy models and sustainable agriculture [10-12].

2.2. Rearing and processing

BSF farming systems ranged from small-scale, household setups to industrial-scale operations capable of processing several tons of waste daily. Essential components of these systems included larval rearing units, adult fly houses for breeding, and waste pre-processing and post-processing facilities [8, 13]. The rearing environment specifically, temperature, humidity, and substrate composition strongly influenced larval growth, survival, and nutrient composition, with optimal conditions yielding high-quality biomass suitable for animal feed [7]. After harvesting, BSF larvae and prepupae could be processed into various products: live larvae for direct feeding, whole dried larvae, defatted meal (after oil extraction), and oil, each with distinct nutritional profiles and applications [14, 15]. Advanced processing methods also enabled the extraction of hydrolyzed proteins, chitin, and chitosan, which have uses in feed, food, pharmaceuticals, and bioplastics [14, 16]. The choice of processing technique such as blanching, freezing, oven- or freeze-drying, mechanical pressing, or supercritical CO_2 extraction affected the quality, stability, and functional properties of the resulting products, particularly the oxidative stability of fats and the purity of protein and chitin fractions [15].

3. Nutritional composition of BSF products

3.1. Proximate analysis

The nutritional composition of BSFL products was highly variable and influenced by factors such as rearing substrate, developmental stage, and processing method. Proximate analysis revealed that BSFL meal typically contained crude protein levels ranging from 40% to 60% on a dry matter basis, with the highest values often observed in defatted or spray-dried products [17, 18]. The amino acid profile of BSFL was notable for its richness in lysine, an essential amino acid often limiting in plant-based feeds, though methionine content was generally lower compared to fishmeal. Lysine was consistently among the most abundant essential amino acids in BSFL meal, with reported values ranging from approximately 2.4% to 3.6% of dry matter, depending on processing methods and rearing substrates [1]. BSFL meal contained a complete spectrum of essential amino acids, frequently fulfilling or exceeding the FAO/WHO criteria for animal and human nutrition table (1) [18, 19].

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The BSFL meal was notable for its rich and balanced mineral profile, with calcium, magnesium, sodium, potassium, phosphorus, zinc, iron, manganese, and copper present in significant amounts. The exact ratios and concentrations could vary depending on the larvae's diet, processing method, and whether the meal was full-fat or defatted. Calcium was the most abundant mineral, often followed by potassium and phosphorus. The Ca:P ratio in BSFL meal typically ranged from 1.1:1 to 2:1, which was favorable for animal nutrition table (2) [18, 20].

Crude fat content in BSFL products varied widely, from 15% to 35%, and was particularly rich in medium-chain fatty acids such as lauric acid (C12:0), which were valued for their antimicrobial properties and energy density. In addition to protein and fat, BSFL contained chitin a structural polysaccharide that acted as a fiber source and prebiotic, supporting gut health and immune function in animals. Mineral content was also significant, with BSFL providing substantial amounts of calcium and phosphorus, often exceeding levels found in conventional protein sources [1, 17, 21].

When compared to traditional feed ingredients like fishmeal and soybean meal, BSFL meal demonstrated a competitive nutritional profile. Fishmeal was typically higher in methionine and overall protein content, but BSFL meal offered a more sustainable and cost-effective alternative with comparable lysine levels and a favourable fatty acid profile [22]. Soybean meal, while rich in protein, was lower in certain essential amino acids and lacked the medium-chain fatty acids present in BSFL. The chitin content in BSFL, absent in fishmeal and soybean meal, provided additional functional benefits as a dietary fiber and prebiotic [1, 21]. The mineral composition of BSFL, particularly its calcium and phosphorus content, further enhanced its value as a feed ingredient. Overall, BSFL meal could serve as a partial or total replacement for fishmeal and soybean meal in animal diets, offering a balanced source of protein, fat, fiber, and minerals, while contributing to the sustainability of animal production systems table (3) [1, 18].

Table 1. Essential amino acid levels in BSFL meal.

Amino acid	Range in BSFL meal (% DM)	Relative abundance
Lysine	2.4 – 3.6	High
Leucine	2.7 – 3.6	High
Valine	2.3 – 3.1	High
Histidine	2.1 – 2.8	Moderate
Threonine	1.4 – 1.9	Moderate
Arginine	1.8 – 2.6	Moderate
Methionine	0.6 – 1.1	Lower
Phenylalanine	1.3 – 2.1	Moderate
Isoleucine	1.8 – 2.4	Moderate

Table 2. Major mineral content and ratios.

Mineral	Full-fat BSFL (g/kg)	Defatted BSFL (g/kg)
Calcium (Ca)	37	57.7
Magnesium (Mg)	4.2	6.2
Sodium (Na)	1.3	1.7
Potassium (K)	12.4	13.4
Zinc (Zn)	61.7	138.1
Iron (Fe)	341.4	529.6
Manganese (Mn)	90.3	128.3
Copper (Cu)	5.6	26.6

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Table 3. Summary of the nutritional comparison of BSFL meal, fishmeal, and soybean meal.

Component	BSFL meal (range)	Fishmeal	Soybean meal
Crude protein (%)	40–60	56–72	44–49
Crude fat (%)	15–35	8–12	1–2
Lysine (g/kg)	23–68	45–70	25–35
Methionine (g/kg)	5–15	15–25	5–8
Chitin (%)	3–9	0	0
Calcium (%)	0.5–2.0	2.5–5.5	0.2–0.4
Phosphorus (%)	0.5–1.0	1.5–3.0	0.6–0.7

4. Applications in livestock and poultry nutrition

4.1. Poultry (Broilers and laying hens)

The application of BSFL in poultry nutrition was extensively studied, revealing promising outcomes for both broilers and laying hens in terms of growth performance, feed efficiency, product quality, and animal health. In broiler chickens, partial replacement of soybean meal with BSFL meal typically at inclusion levels up to 10–15% was shown to maintain or even improve growth performance and feed conversion ratios (FCR). For example, broilers fed diets with 5–10% BSFL meal exhibited similar or slightly higher average weights compared to controls, with no significant differences in daily weight gain or FCR, except for a transient advantage in early growth phases [23-25]. Higher inclusion levels (above 50% replacement of soybean meal protein) could negatively impact feed intake, average daily gain, and carcass quality, indicating that moderate inclusion rates were optimal for maintaining performance and meat yield [26].

Meat quality and sensory attributes were largely unaffected by the inclusion of BSFL meal or fat at recommended levels. Studies reported no significant differences in pH, myoglobin content, water-holding capacity, or cooking loss between broilers fed BSFL and control broilers, and sensory characteristics such as juiciness and taste remained comparable at moderate inclusion rates [27]. However, higher inclusion levels could reduce meat juiciness and taste intensity. They could alter the fatty acid profile by increasing saturated fatty acids (notably lauric acid) and reducing polyunsaturated fatty acids [27, 28]. Importantly, the presence of lauric acid a medium-chain fatty acid abundant in BSFL was linked to beneficial effects on lipid metabolism and energy utilization and could contribute to improved health status in poultry [29].

In laying hens, BSFL meal could be used to partially or completely replace soybean meal without adverse effects on egg production, feed efficiency, or most egg quality parameters. Meta-analyses and controlled studies showed that BSFL supplementation improved feed efficiency, eggshell strength, and specific aspects of albumen quality, while maintaining egg production rates and body weight [30-32]. Yolk color could be affected, with some studies reporting paler yolks at higher BSFL inclusion, while others noted darker yolks depending on the form and level of BSFL product used [33, 34]. The mineral-rich profile of BSFL, particularly its calcium and phosphorus content, could enhance eggshell quality, and the presence of chitin and antimicrobial peptides in BSFL could further support gut health and immune function [29].

A key health benefit of BSFL inclusion was the modulation of gut microbiota. Studies consistently demonstrated that BSFL meal reduced pathogenic bacteria such as Salmonella, Clostridium, and Enterobacteriaceae, while increasing beneficial *Lactobacillus* and *Faecalibacterium* species in the cecal and intestinal microbiota of broilers and laying hens. These changes were attributed to the antimicrobial properties of lauric acid and bioactive peptides present in BSFL, as well as the prebiotic effects of chitin. Improved gut health was associated with enhanced nutrient absorption, immune modulation, and reduced disease risk, supporting overall animal welfare and productivity [35].

4.2. Swine

In swine nutrition, BSFL meal was evaluated as a protein source in both weaner and grower-finisher diets. Research indicated that BSFL meal was palatable to pigs and could support growth performance and feed intake comparable to traditional protein sources [36]. The inclusion of BSFL in pig diets was also associated with improved gut health and immune modulation, likely due to the presence of bioactive compounds such as chitin and antimicrobial peptides, which might reduce intestinal inflammation and support beneficial microbial populations. However, optimal inclusion levels were critical, as excessive amounts could negatively impact nutrient digestibility or growth, particularly in young or immunocompromised animals [36, 37].

Overall, BSFL products offered promising applications in both poultry and swine nutrition, supporting animal performance, product quality, and health, while contributing to the sustainability and resilience of animal production systems.

5. Applications in aquaculture

5.1. A sustainable alternative to fishmeal

The use of black soldier fly larvae meal (BSFLM) as a sustainable alternative to fishmeal in aquaculture has gained significant momentum, driven by the urgent need to reduce reliance on marine-derived feed ingredients and promote circular economy practices. Numerous studies across key aquaculture species including salmon, trout, seabass, tilapia, sturgeon, shrimp, and zebrafish demonstrated that BSFLM could partially or even totally replace fishmeal without compromising growth performance, feed efficiency, or survival rates. For instance, in Nile tilapia, BSFLM substitution up to 100% resulted in no significant differences in growth, feed utilization, or survival compared to fishmeal-based diets, while also improving mucosal immune responses [38]. Similar findings were reported in barramundi, where up to 30% replacement of fishmeal and fish oil with BSFLM and BSF oil maintained growth and feed utilization, and enhanced bactericidal activity, immune gene expression, and mucosal barrier function [39]. In European seabass, partial replacement of fishmeal with BSFLM (up to 50%) improved antioxidative capacity, non-specific immunity, and resistance to Vibrio alginolyticus, with no adverse effects on growth or fillet quality [40, 41]. Studies in rainbow trout, sturgeon, and zebrafish further confirmed that BSFLM could be included at moderate to high levels in aquafeeds without negative impacts on growth, fillet characteristics, or nutrient digestibility, although some changes in fatty acid profiles could occur at higher inclusion rates [42-44].

5.2. Health and disease resistance

Beyond growth and fillet quality, BSFLM offered notable health benefits, particularly through its chitin content and associated bioactive compounds. Chitin, a structural polysaccharide present in BSFLM, acted as a prebiotic and immunostimulant in fish, enhancing gut microflora diversity and activating innate immune responses [45, 46]. Dietary inclusion of BSFLM or isolated chitin was shown to upregulate immune-related genes (such as interleukins and lysozyme), increase the abundance of beneficial gut bacteria, and improve antioxidant status in species like largemouth bass, yellow catfish, and zebrafish [44, 47]. These immunomodulatory effects translated into improved disease resistance: fish and shrimp fed BSFLM or BSF frass exhibited higher survival rates and enhanced resistance to common pathogens, including *Vibrio spp*., *Flavobacterium columnare*, *Streptococcus iniae*, and *Aeromonas hydrophila* [45]. For example, Pacific white shrimp fed diets containing 5–10% BSFLM showed increased body weight, improved immune parameters, and higher survival following Vibrio parahaemolyticus challenge [48]. Similarly, tilapia and seabass fed BSFLM-based diets demonstrated improved complement activity, lysozyme levels, and survival after bacterial challenges [41].

In summary, BSFLM was a viable and sustainable alternative to fishmeal in aquaculture, supporting optimal growth, fillet quality, and survival across a range of species. Its chitin content and associated bioactive compounds conferred additional health and disease resistance benefits, making BSFLM a promising ingredient for the future of sustainable aquafeed production.

6. Applications in companion animal nutrition

6.1. Dogs and cats

The inclusion of BSFL products in companion animal nutrition, particularly for dogs and cats, was extensively evaluated for palatability, nutritional adequacy, functional health benefits, and hypoallergenic potential. Multiple studies demonstrated that BSFL-based diets were highly palatable, with both dogs and cats showing a clear preference for diets containing BSFL meal, oil, or hydrolysates compared to conventional protein sources [49, 50]. This high acceptability was attributed to the unique flavor profile and the presence of short peptides and free amino acids in protein hydrolysates, which enhanced both first-bite and overall intake [51, 52].

Nutritionally, BSFL meal and derivatives provided a complete and balanced protein source suitable for formulating diets that met the requirements of both dogs and cats [53-55]. Studies using extruded and retorted diets with up to 30–37.5% BSFL meal inclusion reported comparable or slightly lower nutrient digestibility than traditional animal proteins, but all values remained within acceptable ranges for pet health [56]. Essential amino acid digestibility was high, though methionine and cysteine could be limiting at higher inclusion rates, necessitating careful formulation. Importantly, BSFL-based diets supported normal growth, maintained healthy body weight, and did not negatively affect blood biochemistry, fecal quality, or overall health in both adult and growing animals [50, 52].

BSFL products also offered functional health benefits. Lauric acid, a medium-chain fatty acid abundant in BSFL fat, was associated with improved skin and coat health, enhanced skin barrier function, and potential anti-inflammatory effects [57, 58]. Studies in dogs showed reduced trans-epidermal water loss and improved skin hydration with BSFL diets, supporting their use in animals with sensitive skin or dermatological issues [57]. Chitin, present in BSFL exoskeletons, acted as a prebiotic fiber, modulating gut microbiota by increasing beneficial bacteria such as *Bifidobacterium* and *Megasphaera*, and reducing potentially harmful genera, thereby supporting gut health and immune function. Antioxidant and anti-inflammatory capacities were also enhanced, as evidenced by increased superoxide dismutase and glutathione peroxidase activities and reduced inflammatory cytokines in both dogs and cats [50, 59]. A notable advantage of BSFL as a novel protein source was its hypoallergenic potential. Protein hydrolysates from BSFL were less likely to be recognized by the immune system, reducing allergenicity and making them suitable for animals with food allergies or adverse food reactions. Preliminary clinical studies in dogs with diagnosed food allergies or dermatitis showed that BSFL-based diets were well tolerated, did not exacerbate pruritic symptoms, and maintained stable body weight and stool quality [50, 60]. Briefly, BSFL products were highly palatable, nutritionally adequate, and functionally beneficial for dogs and cats, with added value as a novel, hypoallergenic protein source for sensitive animals.

7. Beyond nutrition: Emerging veterinary applications

7.1. BSFL for wound debridement (Maggot Therapy)

Beyond their nutritional value, BSFL and their byproducts were gaining attention for innovative veterinary applications, particularly in wound management and sustainable agriculture. In maggot therapy, BSFL were explored as an alternative to the commonly used green bottle fly (*Lucilia sericata*) for wound debridement. A key advantage of BSFL was their selective debridement behavior they preferentially consumed necrotic (dead) tissue while sparing healthy tissue, which reduced the risk of damaging viable cells during treatment. Additionally, BSFL possessed a more robust immune system compared to *L. sericata*, which might lower the risk of septicemia in treated animals by limiting the proliferation of pathogenic bacteria within the wound environment [61]. In-vitro and in-vivo studies, including recent research on mice, demonstrated that topical application of BSFL extracts accelerated wound closure, enhanced cell proliferation, and exhibited strong antibacterial activity, particularly due to the high lauric acid content and the presence of antimicrobial peptides [61, 62]. These findings suggested that BSFL not only facilitated effective debridement but also promoted tissue regeneration and reduced infection risk, supporting their potential as a sustainable and safe alternative in veterinary wound care.

7.2. BSF frass in animal diets

BSF frass, the residue left after larval digestion, was also emerging as a valuable resource in both agriculture and animal husbandry. As a soil amendment, BSF frass was rich in organic matter, beneficial microbes, and nutrients such as phosphorus and potassium. In animal nutrition, early studies indicated that BSF frass might serve as a prebiotic feed ingredient, supporting gut health and immune function in livestock through its content of chitin, bioactive compounds, and beneficial microorganisms [61, 63]. These emerging applications highlighted the potential of BSF-derived products to contribute to sustainable veterinary practices, waste valorization, and improved animal and environmental health.

8. Safety, challenges, and regulatory landscape

8.1. Safety considerations

The safety of BSFL as a feed ingredient hinged critically on the quality and safety of the substrates used for rearing. Substrate safety was paramount, as BSFL could bioaccumulate hazardous substances such as heavy metals (notably cadmium and lead), mycotoxins, pesticides, and veterinary drugs when these contaminants were present in the feedstock. Studies consistently showed that while BSFL could excrete or degrade some contaminants, certain heavy metals and persistent chemicals could accumulate in the larvae, posing risks to animal and potentially human health if not properly monitored [64, 65]. Therefore, only approved, contaminant-free substrates should be used, and regular testing for heavy metals and chemical residues is essential to ensure compliance with feed safety standards [66, 67].

Allergenicity was another safety consideration, particularly for workers handling BSFL. While the risk of allergic reactions in animals consuming BSFL-based feeds appeared low, occupational exposure to insect proteins and chitin could cause sensitization and allergic responses in handlers, underscoring the need for protective measures and monitoring in production facilities [68].

Microbiological safety was a further concern, as BSFL and their substrates could harbor pathogenic bacteria such as *Salmonella*, *Escherichia coli*, *Bacillus cereus*, and *Staphylococcus aureus*, as well as yeasts and molds. The microbial load in larvae was strongly influenced by the type and hygiene of the substrate, as well as rearing and processing conditions. Proper post-harvest processing especially thermal treatments such as blanching or heating above 60°C was shown to reduce or eliminate most pathogens effectively, ensuring the microbial safety of the final product [69-71]. However, spore-forming bacteria like *Bacillus cereus* might require additional control measures [67].

The regulatory landscape for BSFL production was evolving, with many jurisdictions restricting the use of certain waste streams as substrates due to safety knowledge gaps and the potential for contaminant transfer. Comprehensive risk assessments, standardized processing protocols, and clear regulatory frameworks were needed to support the safe and sustainable commercialization of BSFL as animal feed table (4) [68, 72].

8.2. Challenges

The widespread adoption of BSFL as an alternative protein source in animal feed faced several key challenges. One major issue was the standardization of nutritional composition. The nutrient profile of BSFL was highly variable. It depended on factors such as the rearing substrate, temperature, humidity, and larval density, making it difficult to ensure consistent protein, fat, and micronutrient levels in the final product. This variability complicated feed formulation and could impact animal performance, necessitating further research and industry standards to achieve reliable nutritional quality [3, 73].

Cost-competitiveness was another significant barrier. While BSFL production offered sustainability advantages and the potential to convert organic waste into valuable biomass, the current price of BSFL was often similar to or higher than traditional protein sources like fishmeal. High capital and operational costs, the need for a constant supply of suitable organic waste, and challenges in scaling up production all contributed to this issue. Improvements in production efficiency, automation, and supply chain logistics were needed to make BSFL a more economically viable option for large-scale feed applications [74, 75].

Consumer and producer acceptance also played a crucial role in the successful integration of BSFL into animal feed. Despite growing awareness of the environmental benefits, there remained scepticism among both producers and consumers, often due to concerns about the use of insects reared on waste, potential odors, and food safety. Public perception was influenced by cultural attitudes and knowledge gaps, and targeted education and outreach were necessary to improve acceptance of insect-based feeds [2, 76].

8.3. Regulatory status

In the European Union, BSFL was approved for use in aquaculture, poultry, and pig feeds, provided the larvae were reared on substrates that met strict safety criteria, excluding materials like manure and catering waste (EU Regulation 2017/893). In the United States, the Association of American Feed Control Officials (AAFCO) had approved BSFL for use

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in dog and cat food, and for feeding salmonid fish, but only when larvae were raised on feed-grade substrates. Other countries, such as Australia and Canada, had established specific conditions for BSFL use, while many regions with traditional entomophagy were still developing regulatory frameworks. The lack of harmonized global standards and clear legal guidelines remained a challenge for the international trade and commercialization of BSFL-based feeds table (5) [75, 77].

Table 4. Summary of safety, challenges, and regulatory needs for BSFL production.

Safety aspect	Key issues and recommendations
Substrate safety	Use only approved, contaminant-free substrates; monitor for heavy metals, mycotoxins, pesticides, and drugs.
Allergenicity	Risk mainly for handlers; implement protective measures in production facilities.
Microbiological safety	Proper processing (e.g., heating >60°C) is essential to eliminate pathogens; monitor for spore-formers.
Regulatory landscape	Need for clear regulations, risk assessments, and standardized protocols.

Table 5. Summary of challenges and regulatory status for BSFL in feed.

Challenge/Status	Description and current status
Nutritional standardization	Highly variable composition; requires industry standards and research for consistency
Cost-competitiveness	High production costs; price similar to fishmeal; needs efficiency improvements
Consumer/Producer acceptance	Skepticism due to safety, odor, and cultural factors; education needed
Regulatory status (EU)	Approved for aquaculture, poultry, and pigs; strict substrate rules
Regulatory status (US)	AAFCO-approved for dog, cat, and salmonid feeds; feed-grade substrate required
Regulatory status (Other)	Australia, Canada: specific conditions; many countries drafting new regulations

9. Conclusion and future perspectives

BSF has emerged as a viable, sustainable, and multifunctional ingredient with proven benefits across a wide range of animal species, including poultry, fish, swine, and companion animals. Its high protein and fat content, favourable amino acid profile, and presence of bioactive compounds such as antimicrobial peptides and chitin supported not only animal growth and health but also immune modulation and disease resistance. Importantly, BSF production offered a dual advantage: it efficiently converted diverse organic waste streams into valuable protein and fertilizer, thereby addressing both protein shortages and waste management challenges while promoting a circular bio-economy and reducing the environmental footprint of animal agriculture.

Looking ahead, several research priorities were critical to fully realize the potential of BSF. Optimization of rearing substrates was needed to tailor the nutritional profiles of BSF products for specific animal applications and to ensure safety and consistency. Large-scale clinical trials, particularly for wound therapy in veterinary medicine, were necessary to validate the efficacy and safety of BSF-derived products beyond nutrition. Further elucidation of the mechanisms of action of BSF antimicrobial peptides and chitin would enhance understanding of their roles in animal health and unlock new nutraceutical applications. Research into the use of isolated BSF oil and chitin as functional feed additives or nutraceuticals was also warranted, given their antioxidant, anti-inflammatory, and prebiotic properties. Long-term studies on the health impacts of BSF-based diets in companion animals were essential to ensure safety and efficacy over the lifespan of pets. Finally, comprehensive lifecycle assessments and techno-economic analyses were needed to evaluate the commercial viability, scalability, and environmental benefits of BSF production systems, guiding policy and industry adoption.

In summary, BSF stood at the intersection of sustainable protein production and waste valorization, with ongoing

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research poised to expand its applications and solidify its role in future food and feed systems.

Authors' contributions

Heba Hani Ramadan Ahmed and Ashraf Sabry Abdel Fattah El-Sayed wrote and revised the manuscript before submission.

Conflict of interest statement

The authors declare that they have no conflicts of interest.

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Data availability

All the data are available in the manuscript.

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