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A Review of The Potential of Black Soldier Fly (BSF) Maggots as A Sustainable Protein Source to Replace Fish Meal in Animal Feed

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Abstract
Protein is a key component in poultry feed, supporting growth and productivity. Currently, fish meal is the most widely used protein source, but its availability is increasingly limited and its price continues to rise. Black Soldier Fly larvae (*Hermetia illucens*), or BSF maggots, represent a promising alternative protein source to replace fish meal in poultry feed. These larvae contain 40–55% protein, along with essential amino acids, fats, and vital minerals that support chicken health and growth. Rearing BSF larvae uses organic waste as a growth medium, offering environmental benefits by managing organic waste and supporting sustainable livestock production. Various studies indicate that feed based on BSF larvae has good digestibility and competitive feed conversion efficiency in chickens. Furthermore, the use of BSF larvae can enhance the immune system of poultry. Economically, BSF production is relatively efficient and holds significant market potential within the animal feed industry. However, clear production standards and regulations are needed to ensure consistent quality and safety of the feed. Given these advantages, BSF larvae could become a sustainable and effective solution to meet future protein demands in poultry feed.

INTRODUCTION

Protein is a fundamental nutrient in poultry feed, essential for promoting growth, tissue repair, reproduction, and supporting the immune system in chickens (Tran *et al*., 2020; Sembiring & Niassy, 2021). Historically, fish meal has been the predominant protein source in the poultry industry, prized for its complete profile of essential amino acids and high digestibility (Henry *et al*., 2015). However, reliance on fish meal presents significant challenges, including the overexploitation of fish stocks due to overfishing and the sharp rise in global market prices (Tran *et al*., 2020; Sembiring & Niassy, 2021). Developing countries like Indonesia are heavily dependent on imports of this raw material, resulting in increased and volatile feed production costs that threaten the economic viability and sustainability of poultry farming (Salahuddin *et al*., 2024). Consequently, there is an urgent need to develop alternative protein sources that are sustainable, economically feasible, and locally producible to ensure the long-term sustainability of the poultry sector and to support global food security (Smetana *et al*., 2019; FAO, 2022).

In recent years, Black Soldier Fly larvae (*Hermetia illucens*), commonly known as BSF maggots, have emerged as a promising innovative alternative in animal feed production. These larvae are capable of converting various types of organic waste—such as food scraps, agricultural by-products, and animal manure—into biomass rich in proteins and fats. This bioconversion process offers an environmentally friendly and effective approach to organic waste management (Cammack & Tomberlin, 2017; Osuch *et al*., 2024). A critical advantage of BSF larvae is their adaptability to tropical climates and diverse growth substrates, making large-scale rearing highly suitable for regions like Indonesia (Surendra *et al*., 2016; Osuch et al., 2024). The use of BSF larvae not only produces high-quality protein suitable for chicken feed but also contributes to reducing environmental pollution from organic waste, embodying the principles of sustainability in feed production (Gold *et al*., 2018; Van Huis & Oonincx, 2017). Nutritionally, BSF larvae provide complete proteins and essential amino acids necessary for optimal chicken growth (Barroso *et al*., 2017; Dabbou et al., 2018). Although BSF larvae have slightly lower levels of methionine and lysine compared to fish meal, modern processing techniques such as drying and fermentation enhance digestibility and improve the nutritional balance (Spranghers *et al*., 2017; Saidani et al., 2025). The fat content of BSF larvae is rich in lauric acid, known for its antimicrobial properties that can improve digestive health and immune function in poultry (Barroso *et al.*, 2017; University of Massachusetts Amherst, 2025).

Feeding trials have confirmed that substituting fish meal with BSF larvae meal improves feed conversion efficiency, accelerates growth rates, and enhances carcass quality without adverse health effects (Dabbou *et al*., 2018; Saidani et al., 2025). Additionally, bioactive compounds in BSF larvae can modulate gut microbiota and strengthen the immune system of poultry, contributing to improved resilience and productivity (Barroso *et al*., 2017; Spranghers et al., 2017). Economically, BSF farming is highly promising; production can be conducted locally at low cost using abundant, inexpensive organic waste, making it accessible even in small-scale operations (Van Huis & Oonincx, 2017; Singh & Kumari, 2020). This approach reduces dependency on imported feed ingredients that are vulnerable to price volatility and supply disruptions, while simultaneously turning waste into valuable products (Ushakova *et al*., 2021; Osuch et al., 2024). The byproduct of BSF farming, known as frass, serves as a high-quality organic fertilizer to enhance soil fertility and support sustainable agriculture (Bava *et al*., 2019; Ushakova *et al*., 2021). This circular economy model creates new business opportunities for farmers and livestock producers, optimizing resources, improving production efficiency, and increasing income streams (Van Huis & Oonincx, 2017; Singh & Kumari, 2020).

Despite its great potential, the use of BSF as poultry feed faces significant challenges. Variability in larval quality resulting from differences in growth media and farming methods leads to inconsistent nutritional value and safety, posing risks to product reliability (Gasco *et al*., 2020; Lock et al., 2021). Furthermore, regulations governing the use of insect-based feed ingredients remain under development in many countries, including Indonesia, restricting market acceptance and consumer safety assurance (Gasco *et al*., 2020; Verbeke et al., 2020). Negative public and industry perceptions about insect-based feed remain major hurdles that require focused educational and research efforts to overcome (Tanga *et al*., 2021; Verbeke et al., 2020). Therefore, strong collaboration among government agencies, researchers, and industry stakeholders is essential to strengthen regulatory frameworks, support technological advancements in processing, and raise public awareness, enabling BSF to be widely adopted as a safe and effective replacement for fish meal (Gasco *et al.*, 2020; Lock et al., 2021). With ongoing advancements in farming technology and supportive policies, BSF larvae are poised to become a cornerstone of future poultry feed production, contributing significantly to global food security and sustainable development goals (FAO, 2022; Smetana *et al*., 2019).

RESEARCH METHODOLOGY

Based on literature from the past nine years, the use of Black Soldier Fly *(Hermetia illucens)* larvae as chicken feed ingredients shows promising potential. A study by Saidani *et al.* (2025) indicated that the administration of BSF larvae as a partial feed substitute in appropriate doses does not negatively impact broiler chicken growth. They found that providing 5% BSF larvae in the starter phase and 10% in the grower phase can support balanced growth without reducing feed efficiency. This finding is consistent with other studies reporting that the use of BSF larvae hardly reduces chicken growth performance if applied in the right dosage (Huang, 2024; Widyaswara *et al*., 2021).

Furthermore, research by Zamri (2023) and Jan *et al.* (2025) supports the assumption that BSF larvae can be an effective alternative to fish meal, with advantages in organic waste management and production efficiency. They asserted that BSF larvae can be processed from organic waste, which is then converted into high-nutritional feed ingredients, even with a fairly efficient biomass conversion rate during the early growth phase of chickens. The cultivation of these larvae, in addition to reducing feed costs, also contributes to the development of a circular economy and more sustainable livestock industry waste management (Sembiring & Niassy, 2021; Nurkholidza *et al*., 2025).

Moreover, research by Joshi *et al*. (2024) emphasized that BSF larvae given in chicken feed can improve healthy gut microbiota, which has a positive effect on chicken digestion and immune systems. They noted that the administration of BSF larvae has a capacity equivalent to fish meal in supporting immune parameters and digestive health of chickens, without causing significant changes in meat color or texture. Several other studies also show that the total production cost of BSF larva-based feed can be lower, making it an economical and sustainable option for the chicken farming industry at the local and national levels (Khamis & Bakar, 2018; accessed from the web).However, large-scale application still requires standardization of BSF larvae cultivation and processing to ensure consistent nutritional quality. Some studies suggest the need for stricter regulations on the production process and safety of insect-based feed. The development of drying, fermentation, and feed formulation technologies must be optimized to ensure the stability and safety of the final product, so that it can be widely accepted by industry and consumers in the future (Hwangbo *et al.*, 2009; Chia et al., 2021). Therefore, cooperation between the government, industry players, and academics is very important so that BSF larvae can play a role as a viable and sustainable alternative protein source in the future.Overall, this review demonstrates that Black Soldier Fly larvae are an innovative solution with great potential in improving the sustainability of the chicken feed industry. Its application not only helps meet protein needs but also contributes to efficient waste management and reduced environmental impact from the use of conventional raw materials. With appropriate regulations and technological innovations, BSF larvae can be integrated as an efficient and environmentally friendly main feed ingredient, supporting steps towards food security and global sustainable development (Jan *et al*., 2025; Sembiring & Niassy, 2021).

RESULTS AND DISCUSSION

Nutritional Composition of Black Soldier Fly (BSF) Larvae

Recent research from 2018 to 2025 continues to support that *Hermetia illucens* larvae are a highly promising alternative protein source for animal feed. The larvae consistently show high values of crude protein and lipid on a dry matter basis, typically ranging from **400 to 600 g per kg** for protein and **200 to 300 g per kg** for lipid (Rahman *et al*., 2024; Ogello *et al*., 2025). These figures place BSF larvae within a competitive range compared to high-quality fish meal, which often contains between 550 and 650 g protein per kg. Beyond macronutrients, BSF larvae are rich in essential minerals including calcium (Ca), phosphorus

(P), magnesium (Mg), and iron (Fe), supporting functions like bone formation, enzymatic reactions, and metabolic regulation (Imathiu *et al*., 2022). Their amino acid profiles include lysine, methionine, threonine, and other nutritionally important amino acids, albeit methionine and lysine levels tend to be slightly lower than those in fish meal (Mutungi *et al*., 2021).

More detailed analyses in recent studies have refined our understanding of BSF larvae's composition. A review of the nutritional composition of BSF larvae shows that among essential amino acids, leucine (~44.6 g/kg average), lysine (~38.8 g/kg), and valine (~40.1 g/kg) are among the most abundant (on a dry matter basis) in both full-fat and defatted larvae. These levels often surpass those in soybean meal; however, methionine and tryptophan remain among the least abundant essential amino acids and are notably lower than in fish meal (as reviewed by *Nutritional Composition of Black Soldier Fly Larvae*, 2022). Another study of BSF larvae meal demonstrated that lysine ranges between 1.76 % and 2.41 % (on a DM basis), leucine between 1.46 % and 2.11 %, and valine between 1.41 % and 1.77 % across different drying methods (F1000Research, 2024). In that same work, the fatty acid composition was dominated by lauric acid (22.07–24.88 %), palmitoleic acid, and linolelaidic acid, reflecting a relatively balanced fatty acid profile for energy supply and possible functional lipid contributions (e.g. immune modulation).

The mineral profile across recent studies confirms that BSF larvae are rich in multiple trace and macro minerals. For example, in one compositional review, calcium content ranged widely (1.2 to 35.7 g/kg), iron up to 191 g/kg in some cases, magnesium 1.0–3.5 g/kg, phosphorus 1.0–10.3 g/kg, and other elements like copper, sodium, potassium, manganese, and zinc also present in measurable amounts (as summarized in *Nutritional Value of Black Soldier Fly Larvae* review). These mineral levels provide a solid basis for larval use in feed, though care must be taken to balance mineral ratios, ensure bioavailability, and avoid excesses or imbalances.

However, one limitation is the presence of chitin in the larvae's exoskeleton, which can reduce apparent protein digestibility by binding proteins or interfering with enzymatic access (BSFL have ~6.89 % nitrogen in chitin matrices). Because of this, post-harvest treatments like defatting, microbial fermentation, enzymatic hydrolysis, and careful thermal processing are often used to improve digestibility and reduce chitin interference. For example, defatted BSF flour has been shown to reach protein concentrations of 55–58 % with fat reduced to 4–6 %, which improves storage stability and eases handling (Azmi *et al*., 2022). Fermentation by *Lactobacillus* species has demonstrated reductions in chitin content and improved feed conversion in poultry and aquaculture species (Nyakeri *et al*., 2023). In addition, substrate selection plays a significant role: Deshmukh *et al*. (2024) found that substrates such as fruit residues, vegetables, or livestock manure yield different larval compositions in terms of fat, protein, and ash content. Saputra and Lee (2023) further observed that defatted larvae had enhanced mineral concentrations (e.g. Ca, Fe, Mg) compared to full-fat larvae. Chen *et al*. (2023) reported that diet formulations not only affect larval growth and composition but also reshape gut microbial communities and digestive enzyme activity, thereby influencing conversion efficiency.

A recent study exploring amino acid nutrition in BSF larvae showed that reductions in single amino acids in substrates did not necessarily impair larval performance, implying flexibility or compensatory metabolic mechanisms (Rethinking Amino Acid Nutrition of BSF, 2024). In that experiment, crude protein content (on DM basis) ranged from 42.8 % to 46.7 % depending on amino acid manipulation, with lysine content remaining between ~2.0 % and ~2.32 % and a relatively narrow lysine-to-CP ratio (~4.9–5.1 %) (MDPI, 2024). These findings indicate that BSF larvae have some adaptability in amino acid utilization and perhaps a buffer against substrate variation.Taken together, the nutritional evidence strongly supports the viability of BSF larvae as a high-quality protein and lipid source, though practical considerations around chitin, substrate effects, processing, and amino acid balancing must be addressed to maximize performance in feed formulations

Comparison with Conventional Fish Meal

Fish meal has long been considered the gold standard protein ingredient for animal feeds, thanks to its high digestibility, favorable amino acid profile, and consistency. Yet, recent experimental and meta- analytic evidence increasingly suggests that BSF meal, when properly processed and formulated, can approach or even match fish meal in several performance and digestibility metrics. In controlled trials, protein digestibility of BSF meal often falls in the range of **85–90 %**, comparable to fish meal under similar testing conditions (Tschirner *et al*., 2021; Rahman *et al*., 2024). Broiler feeding studies show that replacing up to 10 % of fish meal with BSF meal does not significantly reduce growth rate, feed conversion ratio (FCR), or carcass yield (Ogello *et al*., 2025). In aquaculture, research has similarly shown that BSF meal can support comparable feed utilization and growth efficiency when essential amino acids are properly balanced (Le Boucher *et al*., 2024).

The digestibility advantage is further bolstered by appropriate processing. Enzymatic pretreatment and micronization break down chitin and physical barriers, increasing accessibility of amino acids (Azmi *et al*., 2022; Kim et captured by Kim *et al*., 2023). In swine, defatted BSF meal achieved standardized ileal digestibility values close to those of soybean meal and fish meal, suggesting its robust potential for inclusion in pig diets (Kim *et al*., 2023). Additionally, solubility studies in Atlantic salmon have shown high in vivo protein digestibility (~99 %) and strong correlations between in vitro and in vivo solubility when appropriately standardized (Gopika Radhakrishnan *et al*., 2022).

However, it’s worth noting that a recent meta-analysis of BSF in aquafeeds observed that BSF generally contains lower proportions of several essential amino acids compared to fish meal, especially lysine and methionine (5.6–6.4% and ~1.7% of total protein, respectively) (systematic meta-analysis on BSF, 2023) . This suggests that full replacement of fish meal in many diets still demands supplementation or ingredient blending to meet amino acid requirements.

Economic Potential of BSF Production

The economic prospects of BSF cultivation are highly favorable due to its low input requirements and the possibility of using waste materials as feed substrates. Fish meal prices have continued to rise— exceeding IDR 15,000 per kilogram in recent years—mainly due to overfishing and volatile market dynamics (Rahman *et al*., 2024). In contrast, BSF larvae can be produced locally using abundant organic waste, including agricultural residues, food waste, and livestock manure, creating a circular economy model that transforms waste into valuable feed protein (Imathiu *et al*., 2022). Efficiency analyses show that BSF larvae convert 15–20% of organic waste into biomass, yielding 150–200 kg of dry larvae per ton of waste processed (Ogello *et al*., 2025).

Economic feasibility studies indicate that the by-products of BSF production, particularly the residue known as frass, contribute additional revenue streams. BSF frass serves as an organic fertilizer rich in nitrogen (N), phosphorus (P), and potassium (K), which enhances soil fertility and can replace synthetic fertilizers (Azmi *et al*., 2022). The production system requires minimal land and water compared with fish or soybean meal, further reducing environmental costs. A meta-analysis by Tan *et al*. (2023) concluded that BSF farming could reduce feed costs by up to 25–30%, depending on the scale of operation and the availability of local waste materials. This makes BSF farming particularly attractive for smallholder farmers and feed cooperatives in tropical regions such as Indonesia, Malaysia, and Thailand, where waste accumulation and feed import dependency are major economic challenges.

Environmental and Sustainability Aspects

BSF production is recognized as an environmentally sustainable approach that addresses both waste management and feed security. Life Cycle Assessment (LCA) studies have shown that BSF protein production emits less than 1 ton CO_2-equivalent per ton of wet larvae, which is significantly lower than emissions associated with fish meal or soybean meal (Ndeh *et al*., 2024). BSF larvae can decompose 50– 70% of organic waste within 10–14 days, effectively diverting large amounts of waste from landfills and reducing methane (CH_4) and nitrous oxide (N_2O) emissions (Rahman *et al*., 2024). Furthermore, the residue from BSF farming—frass—is a nutrient-rich organic fertilizer that improves soil fertility and reduces the reliance on chemical fertilizers (Imathiu *et al*., 2022).

In tropical regions such as Indonesia, BSF can be reared year-round due to favorable climatic conditions, ensuring stable production and continuous waste recycling (Nyakeri *et al*., 2023). A recent Indonesian LCA study conducted by Fathurrahman *et al*. (2023) found that BSF-based waste management systems reduced greenhouse gas emissions by more than 60% compared to conventional composting. Similarly, Bava *et al*. (2019) demonstrated that substituting fish meal with BSF meal in livestock feed formulations can reduce overall carbon footprint by up to 47%. Hence, BSF farming not only promotes circular bioeconomy principles but also aligns closely with global climate action initiatives targeting sustainable food production and waste reduction.

Technological and Quality Challenges

Despite its clear advantages, BSF production faces several technological and quality control challenges that must be addressed to ensure scalability and safety. Nutrient composition in BSF meal can vary widely depending on substrate type, larval age, rearing density, and processing technique (Azmi et al.,2022). Moreover, substrate contamination by heavy metals, pesticide residues, or pathogens can pose potential food safety risks if not carefully monitored (Rahman et al., 2024). Therefore, strict safety standards and quality control procedures—including substrate selection, sterilization, and drying—are essential to guarantee feed quality.

Technological innovations have focused on improving product consistency and digestibility through enzymatic hydrolysis, microbial fermentation, and defatting processes (Ndeh et al., 2024). These techniques can enhance protein solubility and reduce chitin content, which often interferes with amino acid absorption in animals. Automation and precision-controlled environmental systems have also improved production efficiency. According to Ogello et al. (2025), optimizing larval density, substrate composition, and moisture content can increase yield by 20–25%. In addition, emerging research into genetic strain selection and microbiome engineering offers new opportunities to standardize the nutritional quality of BSF larvae (Deshmukh et al., 2024). However, comprehensive regulation and certification frameworks are still needed to ensure consumer confidence and international trade compliance.

Market Acceptance and Policy Implications

Although the technical and environmental potential of BSF-based products is substantial, market acceptance remains a key factor limiting large-scale adoption. Recent studies indicate that psychological, cultural, and social factors play significant roles in determining how insect- based feeds are perceived, particularly in societies unfamiliar with insect utilization (Syartiwidya et al., 2025). For instance, surveys in several Asian countries revealed that while farmers and feed producers recognize BSF as a promising protein alternative, end consumers (e.g., buyers of fish, chicken, and eggs) often hesitate due to the perception that humans indirectly "consume insects," which are associated with unhygienic conditions.

Research published in Animal (2023), titled "Recent Advances in Insect-Based Feeds: From Animal Farming to the Acceptance of Consumers and Stakeholders," highlighted that transparent field demonstrations and trials can reduce consumer uncertainty by showcasing microbiological safety, consistent quality, and animal health benefits of BSF feed. Labeling and traceability also play vital roles, as consumers are more likely to trust products with verified substrate sources, safety certifications, and assurances of being free from heavy metal contamination.

Regulatory frameworks in Southeast Asia are evolving to accommodate the insect feed industry. A 2023 study titled "From the Heart of the Animal Feed Industry: A Southeast Asian Perspective on Insects for Feed in Asia" reported that countries such as Thailand, Indonesia, Malaysia, and the Philippines are making progress in standardization and cross-sector collaboration despite ongoing challenges in raw material regulation, safety approvals, and trade policies. Government incentives—including subsidies, infrastructure investment, and research grants—could further accelerate BSF technology adoption and reduce entry costs for small producers.Moreover, regulatory policies must encompass comprehensive feed safety standards covering microbial, heavy metal, and pesticide residue limits, along with clear post-harvest processing and substrate management protocols. Differences in national standards currently hinder international trade in BSF products. Systematic reviews (Environment, Development and Sustainability, 2024) have emphasized the urgent need for harmonized safety data and regulatory alignment across regions.Public policy support through educational campaigns and transparent communication regarding the sustainability and safety of BSF feed will be crucial to overcome stigma. Governments integrating BSF systems into food security, waste management, and climate policies will establish a strong foundation for industrial growth and international competitiveness.

Climate Change Mitigation Potential

BSF farming contributes directly to climate change mitigation beyond simply reducing emissions from conventional feed sources. By converting organic waste into BSF biomass, this system can drastically cut methane (CH_4) and nitrous oxide (N_2O) emissions from decomposing waste in landfills. Systematic reviews have shown that BSF farming can lower methane emissions by 50–70%, depending on substrate and rearing conditions (Future Opportunities, 2024). Field studies in Southeast Asia further demonstrate that BSF-based feeds have significantly smaller carbon footprints than fishmeal or imported soy-based diets (Insect Farming for Food and Feed in the Global South, 2024).

Additionally, BSF frass used as organic fertilizer reduces reliance on synthetic fertilizers—major contributors to N_2O emissions due to fossil-fuel-dependent production processes. Locally produced BSF feed systems also improve resilience by minimizing dependence on volatile global trade and marine resources affected by overfishing and extreme weather. Studies optimizing substrate and rearing conditions (humidity, temperature) confirm that BSF productivity can be maintained even under challenging tropical climates (Optimizing Black Soldier Fly Production: Substrate Variation, 2025).

Future Prospects and Integration in Livestock Systems

Looking ahead, the integration of BSF production into large-scale livestock and cross-sector systems presents significant opportunities. Long-term feeding trials are needed to evaluate the effects of BSF meal on animal health, productivity, and product quality (e.g., meat, eggs, fish), as well as residue accumulation. For example, the 2023 study "Sustenance Trial to Analyze the Effects of Black Soldier Fly Larvae Meal on the Reproductive Efficiency of Sows and the Hematological Properties of Suckling and Weaning Piglets" found that replacing conventional protein with BSF meal did not reduce reproductive efficiency in sows and had minimal effects on piglet hematological parameters, although optimization of chitin removal and inclusion ratios was recommended.

Research on aquatic and monogastric species should also employ reproducible, standardized designs. The 2025 paper "Broad Acceptance of Sustainable Insect-Based Shrimp Feeds Requires Reproducible and Comparable Research" emphasized that variations in shrimp feed trials often result from inconsistencies in pre-treatment methods, experimental designs, and statistical analyses rather than nutritional content alone.Technological advancements such as automation, environmental control systems, and optimized substrates will continue to improve efficiency and product quality. Selective breeding of BSF strains adapted to local climates and resistant to pathogens may become a breakthrough innovation. Economic scalability remains crucial; integrated BSF industries encompassing organic waste collection, larval production, processing, and feed distribution must meet quality and safety standards to earn user and consumer trust.International collaboration is equally vital to harmonize safety standards, share technology, and expand access for small and medium enterprises. Ultimately, incorporating BSF into national agricultural sustainability and food system policies will support waste management, emission reduction, and local protein availability. With proper regulation, public awareness, and continued research, BSF farming can become a cornerstone of a sustainable, resilient, and environmentally responsible global food production system.

CONCLUSIONS AND SUGGESTION

Black Soldier Fly (BSF) larvae offer a sustainable, economical, and environmentally friendly protein source to replace fish meal in animal feed. Their high nutritional value, waste conversion efficiency, and potential to reduce environmental impacts make them ideal for future feed systems. To maximize their use, standardization of production, safety regulations, and public awareness are needed to ensure quality, safety, and broad market acceptance.

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