



# Black Soldier Fly Larvae Meal as a Sustainable Alternative Meal Supplementation: A Review

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## ABSTRACT

Black soldier fly larvae meal (BSFLM) is increasingly recognized as a sustainable alternative to conventional protein sources such as fishmeal and soybean meal, with added value in organic waste recycling. This review synthesizes current evidence on Black Soldier Fly (*Hermetia illucens*) production systems, nutritional characteristics, environmental performance and applications in feed, food and circular economy models. BSFLM typically contains 40-45% crude protein and 25-35% lipids (dry matter basis), with a favorable amino acid profile for animal nutrition. Life cycle assessments indicate that replacing fishmeal or soybean meal with BSFLM can reduce greenhouse gas emissions by 30-40%, while requiring substantially less land and water. Feeding trials across aquaculture and poultry commonly show that partial substitution (25-50%) maintains growth performance and product quality. In addition, BSFLM can reduce organic waste mass by 50-80%, generating frass suitable for reuse as fertilizer.

**Key words:** Black soldier fly larvae meal, Circular economy, Protein alternative, Sustainable feed, Waste recycling.

The Black Soldier Fly (*Hermetia illucens*) has emerged as a highly efficient insect for waste recycling and as a sustainable source of protein for animal feed, food products and industrial applications (Tomberlin *et al.*, 2009; Huis and Tomberlin, 2017). Historically, the use of insects as food and feed has been practiced in various cultures, but the commercial cultivation of black soldier fly larvae meal (BSFLM) has only recently gained widespread attention as a solution to the growing global challenges of food security, environmental sustainability and waste management (FAO, 2021).

The black soldier fly larvae (BSFL) are part of the Diptera order and are naturally attracted to decaying organic matter, which they efficiently transform into protein-rich larvae. The larvae's ability to feed on a wide range of organic waste products, including food scraps, agricultural by-products and even animal manure, makes them an environmentally friendly option for recycling organic waste while simultaneously providing a nutritious protein source for animal feed (Diener *et al.*, 2011). This unique combination of waste management and high-protein meal production has drawn significant interest globally as a sustainable alternative to conventional feed ingredients like soybean and fish meal, which are resource-intensive and have a high environmental footprint (Makkar *et al.*, 2014).

In recent years, multiple studies have demonstrated the high nutritional value of BSFLM, noting that it is rich in protein, essential fatty acids and micronutrients like calcium, phosphorus and iron (Barragan-Fonseca *et al.*, 2017). For instance, research in Brazil and China has shown that BSFLM can be used successfully as a substitute for fishmeal in aquaculture diets, improving fish growth rates without negatively affecting feed efficiency or animal health (St-Hilaire *et al.*, 2007; Zhou *et al.*, 2013). Trials on

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eels and loach fish report maintained growth and acceptable meat quality when fishmeal is partially or wholly replaced by BSFLM (Nguyen and Tran, 2025; Nguyen and Tran, 2024). Trials on poultry have also shown comparable growth and meat quality with BSFLM substitution meal (Nguyen and Tran, 2024). These findings underscore the potential of BSFLM to address some of the key challenges in global food production.

BSFLM is increasingly referred to as a "sustainable alternative meal" because of its ability to replace conventional protein sources such as fishmeal and soybean meal, which are resource-intensive and environmentally damaging. Soybean cultivation, for instance, contributes to deforestation and biodiversity loss in South America, while requiring high water inputs and fertilizer use (Makkar *et al.*, 2014; Smetana *et al.*, 2016). Fishmeal production, on the other hand, relies heavily on overfished wild stocks, raising ecological concerns about marine ecosystem depletion (FAO, 2021). In contrast, BSFLM can be reared on organic waste substrates such as food scraps and agricultural by-products, thereby lowering

land and water demand while simultaneously addressing waste disposal challenges (Diener *et al.*, 2011; Smetana *et al.*, 2019). Comparative life cycle assessments (LCAs) suggest that substituting fishmeal or soybean meal with BSFLM can reduce greenhouse gas emissions by approximately 30-40% and land use by more than 70%; however, these estimates vary depending on system boundaries, substrate selection and production scale and may differ substantially between attributional and consequential LCA approaches (Smetana *et al.*, 2016; Smetana *et al.*, 2019; Parodi *et al.*, 2020). Feeding trials have also demonstrated that partial substitution (25-50%) of fishmeal with BSFLM in aquaculture diets sustains growth performance without negative health effects (St-Hilaire *et al.*, 2007; Zhou *et al.*, 2013). These findings clarify why BSFLM is described as a “sustainable alternative meal,” combining nutritional adequacy with tangible environmental benefits. Moreover, the environmental sustainability of BSFL is a major driver of its adoption. The production of BSFLM requires significantly less land, water and energy compared to traditional livestock farming and it can help mitigate issues related to waste disposal (Smetana, Schmitt and Mathys 2019). For example, in Europe and the United States, BSFL are already being used in waste management systems to process food waste, reducing landfill use and lowering methane emissions (Parodi *et al.*, 2020; Diener *et al.*, 2009). Aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), BSFLM offers a nature-based solution to the intertwined challenges of food security, waste reduction and climate change (Ramzy *et al.*, 2025; Akwa *et al.*, 2025; Sarangi *et al.*, 2024).

As the global population continues to grow, the demand for alternative protein sources is expected to rise. The United Nations has recognized insects, including BSFLM, as a key component of sustainable food systems for the future, as they offer a solution to both the growing protein demand and environmental constraints posed by traditional livestock production (FAO, 2021; Huis and Tomberlin, 2017). This review aims to explore the various potential of BSFLM, focusing on its production, nutritional benefits, environmental advantages and applications in animal feed and waste management, while also addressing the challenges that remain in scaling its global use.

This manuscript is a narrative review synthesizing current evidence on BSFLM production, nutritional composition, sustainability performance and applications in feed, food and circular economy systems. Literature was identified through targeted searches of peer-reviewed articles, review papers and institutional reports relevant to insect-based protein production and BSFLM systems. Key search terms included combinations of “Black Soldier Fly,” “*Hermetia illucens*,” “larvae meal,” “insect protein,” “fishmeal replacement,” “soybean meal replacement,” “life cycle assessment,” “GHG emissions,” “land use,” “waste bioconversion,” “frass,” “safety,” and “allergenicity.”

Priority was given to studies providing quantitative outcomes, including reported ranges for nutritional composition (e.g., crude protein, lipid content, mineral profiles), substitution levels in feeding trials and sustainability indicators derived from life cycle assessment (LCA) studies.

Evidence was organized into thematic sections (biology and production processes, applications in animal feed, human nutrition, waste management, safety considerations and prospects). To improve conciseness and reduce repetition across sections, quantitative findings that were consistently reported in multiple sources were extracted and consolidated into summary tables. These tables present typical value ranges and commonly tested substitution levels, while the narrative text emphasizes interpretation, variability drivers (such as substrate choice, processing intensity, production scale) and limitations. Environmental impact claims were interpreted cautiously, recognizing that LCA outcomes depend on methodological choices such as system boundaries and the distinction between attributional and consequential approaches.

### Biological characteristics and production processes

The Black Soldier Fly is a member of the family Stratiomyidae, native to the Americas but now distributed globally in tropical and temperate regions (Tomberlin *et al.*, 2002). Adults are non-pest flies that do not feed and are harmless to humans and livestock. Instead, they rely on energy reserves accumulated during the larval stage (Sheppard *et al.*, 2002).

The larval stage is the most important from a production perspective. BSFL exhibit rapid biomass accumulation, reaching 25-30 mm in length and a mass of up to 200 mg per larva within 14-18 days under optimal conditions (Diener *et al.*, 2009). Their diet is highly flexible, encompassing a wide range of organic substrates such as food waste, agricultural by-products, animal manure and even certain industrial residues (Surendra *et al.*, 2016). These larvae are thermophilic and perform best at temperatures between 27-30°C, relative humidity levels above 60% and with adequate substrate moisture (Cammack and Tomberlin, 2017). They display a high feed conversion efficiency and can reduce organic waste mass by 50-80% while simultaneously producing high-quality protein (up to 42-45% crude protein) and lipids (30-35%) on a dry matter basis (Barragan-Fonseca *et al.*, 2017). In addition to macronutrients, BSFL contain valuable micronutrients, including calcium, phosphorus and iron, which are beneficial in animal nutrition (Makkar *et al.*, 2014).

Commercial BSFL production systems follow a cyclical process comprising:

#### Breeding and egg collection

Adult flies are maintained in breeding cages with access to light (natural or artificial) to stimulate mating. Females oviposit clusters of 500-900 eggs in crevices near but not directly on the feeding substrate. Egg collection devices made of corrugated cardboard or wooden slats are commonly used (Tomberlin *et al.*, 2009).

### Larval rearing

Collected eggs hatch within 3-4 days and neonate larvae are transferred to rearing trays containing pre-processed organic waste. The larvae are allowed to feed for 10-14 days until they reach the late instar stage. Substrate depth, moisture content (around 60-70%) and feeding rate are carefully monitored to optimize growth and prevent anaerobic conditions (Diener *et al.*, 2011).

**Harvesting** - When larvae reach the prepupal stage, they self-migrate from the feeding substrate in search of dry pupation sites. This behavior is exploited using self-harvesting ramps. Alternatively, larvae can be separated mechanically using sieves (Chia *et al.*, 2018).

### Processing into meal

Harvested larvae are typically killed by blanching, microwaving, or freezing, followed by drying using ovens, solar dryers, or fluidized bed dryers. The dried larvae are then mechanically pressed to extract oil, with the remaining defatted biomass milled into BSFLM (Spranghers *et al.*, 2017).

### By-product utilization

The residual frass (insect manure and undigested substrate) is rich in organic matter and can be used as a soil amendment or organic fertilizer, contributing to nutrient cycling and sustainable agriculture (Meneguz *et al.*, 2018). Although BSFLM is among the most commercially scalable insect-derived proteins, its nutritional and functional profile differs meaningfully from other insect meals such as mealworm (*Tenebrio molitor*) and cricket meals, which are also being explored for feed and food applications. Compared with many other edible insects, BSFLM often contains a relatively higher lipid fraction and substantial levels of medium-chain fatty acids such as lauric acid, which may provide added antimicrobial functionality in livestock and aquaculture systems. In contrast, mealworm and cricket meals are frequently characterized by higher consumer acceptability in human food contexts due to their established presence in the edible insect market, but their production may rely more heavily on higher-quality feed inputs, limiting circular-economy advantages when compared with BSFLM systems. From a sustainability perspective, environmental impacts vary across insect species and production chains, with outcomes strongly influenced by rearing substrate, energy use in drying and scale of

operation; therefore, no single insect meal can be considered universally superior across all contexts. Instead, BSFLM's strongest comparative advantage lies in its ability to convert low-value organic waste streams into high-value biomass, positioning it as a particularly relevant candidate for integrated waste-to-feed circular systems, while other insect meals may remain more competitive in specialized food-grade or niche markets depending on regional regulatory and consumer conditions (Smetana *et al.*, 2023; Meyer-Rochow *et al.*, 2021). Modern industrial-scale facilities are increasingly employing automated rearing systems with climate control, conveyor-based feeding and AI-driven monitoring of larval growth, enabling year-round production and consistent quality (Huis and Tomberlin, 2017).

Analytical characterization of BSFLM has confirmed its suitability as a protein-rich feed ingredient. On a dry matter basis, crude protein content ranges from 40-45%, with lipids at 25-35% depending on the rearing substrate (Barragan-Fonseca, Dicke and van Loon, 2017; Spranghers *et al.*, 2017). The amino acid profile is favorable for animal nutrition, particularly in lysine and methionine, which are often limiting in plant-derived proteins (Makkar *et al.* 2014). BSFLM is also a source of essential minerals, including calcium (5-8%), phosphorus (0.6-1.0%) and iron, which are critical for bone development and metabolic functions (Meneguz *et al.*, 2018). Importantly, substrate composition influences nutrient output, with larvae reared on high-protein wastes exhibiting elevated protein yields, while lipid levels increase on carbohydrate-rich substrates (Spranghers *et al.*, 2017). These compositional insights are crucial for tailoring BSFLM applications across feed and food sectors. The nutritional composition of BSFLM reported across the literature is summarized in Table 1, highlighting typical ranges for crude protein, lipid content, key minerals and nutritionally relevant amino acids.

## Applications and influences

### Animal feed

BSFLM is increasingly recognized as a sustainable and nutrient-dense alternative to conventional protein sources such as fishmeal and soybean meal. A comparative synthesis of BSFLM, fishmeal and soybean meal is provided in Table 2 to highlight differences in nutritional role, sustainability implications and supply-chain constraints (Makkar *et al.*, 2014; Smetana *et al.*, 2016; Smetana *et al.*, 2019;

**Table 1:** Nutritional composition of BSFLM (dry matter basis).

| Component     | Range                      | Notes                                                     | References                                                             |
|---------------|----------------------------|-----------------------------------------------------------|------------------------------------------------------------------------|
| Crude protein | 40-45%                     | Varies with substrate and processing                      | Barragan-Fonseca <i>et al.</i> , 2017; Spranghers <i>et al.</i> , 2017 |
| Lipids        | 25-35%                     | Higher on carbohydrate-rich substrates; lower if defatted | Spranghers <i>et al.</i> , 2017                                        |
| Calcium       | 5-8%                       | Relatively high vs plant meals                            | Meneguz <i>et al.</i> , 2018                                           |
| Phosphorus    | 0.6-1.0%                   | Important for bone development                            | Meneguz <i>et al.</i> , 2018                                           |
| Amino acids   | High lysine and methionine | Often limiting in plant-derived proteins                  | Makkar <i>et al.</i> , 2014                                            |

EFSA, 2015; Parodi *et al.*, 2020; Barragan-Fonseca *et al.*, 2017).

On a dry matter basis, BSFLM typically contains 40-45% crude protein and 25-35% lipids, with a balanced amino acid profile rich in lysine and methionine—two amino acids often limiting in plant-based feeds (Barragan-Fonseca, Dicke and van Loon, 2017; Makkar *et al.*, 2014). Numerous studies have shown its effectiveness in livestock, poultry and aquaculture diets. For example, in walking catfish (*Clarias magur*), it was reported that a 50% replacement of fishmeal with BSFLM produced the highest final mean weight (52.67 g) and the lowest feed conversion ratio (2.10), alongside improved hematological indices, supporting BSFLM as a viable partial substitute in carnivorous freshwater species (Bordoloi *et al.*, 2025). Another study demonstrated that substituting 25-50% of fishmeal with BSFLM in rainbow trout (*Oncorhynchus mykiss*) diets did not compromise growth performance or feed conversion ratio (St-Hilaire *et al.*, 2007). Similarly, gut health and immune responses were improved in broiler chickens fed BSFLM-supplemented diets (Schiavone *et al.*, 2019). BSFLM also has antimicrobial peptides and lauric acid, which can help reduce pathogenic bacterial loads in animals (Elhag *et al.*, 2017). In broiler production, a dose-dependent response has also been reported, where 25% replacement of soybean meal using BSFLM improved performance indicators, while higher replacement levels (35-50%) were less beneficial and in some cases counterproductive, likely due to digestion and absorption constraints (Sampathkumar *et al.*, 2026).

Reported BSFLM substitution levels across major livestock and aquaculture systems are summarized in Table 3, with emphasis on commonly tested replacement ranges and performance outcomes.

Numerous feeding trials have demonstrated the supplementation potential of BSFLM in diverse animal species beyond single-species substitution studies. In poultry production, replacing 10-25% of soybean meal with BSFLM not only sustained growth rates but also improved feed conversion efficiency and carcass quality, linked to lauric acid's antimicrobial properties (Schiavone *et al.* 2019). In aquaculture, eel and loach diets supplemented with BSFLM in place of fishmeal maintained growth performance while preserving acceptable meat quality (Nguyen and Tran, 2025). In rainbow trout, partial substitution (25-50%) of fishmeal with BSFLM produced growth rates comparable to fish fed conventional diets (St-Hilaire *et al.*, 2007). Such findings reinforce BSFLM's role as a supplementation strategy that not only replaces conventional protein inputs but also contributes functional bioactive compounds that enhance gut health and disease resistance. These results underscore the adaptability of BSFLM in diverse feeding systems and its potential to reduce reliance on conventional feed ingredients without compromising animal health or productivity.

#### Human nutrition

While most current production is for animal feed, BSFLM has been investigated as a novel food ingredient for human consumption, particularly in high-protein snacks, baked goods and protein powders. Its protein digestibility-corrected amino acid score (PDCAAS) is comparable to traditional animal proteins such as beef and chicken (Huis and Tomberlin, 2017).

Pilot studies in Europe and Asia have demonstrated the feasibility of incorporating BSFLM into human food products such as biscuits, pasta and bread, often increasing protein content by 20-30% without significantly affecting sensory attributes (Tzompa-Sosa *et al.*, 2023).

**Table 2:** Comparative overview of BSFLM, fishmeal and soybean meal.

| Dimension                    | BSFLM                                                              | Fishmeal                                        | Soybean meal                                              |
|------------------------------|--------------------------------------------------------------------|-------------------------------------------------|-----------------------------------------------------------|
| Primary role                 | Alternative protein + circular bioconversion output                | High-quality animal protein                     | Plant protein staple                                      |
| Sustainability profile       | Potentially strong when waste-based; depends on energy + substrate | Linked to wild fish stocks; over-fishing risk   | Linked to deforestation, biodiversity loss, high land use |
| Circular economy value       | High (waste-to-feed + frass fertilizer)                            | Low                                             | Moderate (crop systems, but not waste-based)              |
| Key nutritional strengths    | High protein; functional lipids; minerals (Ca)                     | Excellent amino acid profile; highly digestible | Stable protein source; widely available                   |
| Main limitations             | Composition variability; safety depends on substrate; regulation   | Supply volatility; ecological pressure          | Land and water demand; fertilizer/pesticide reliance      |
| Typical replacement evidence | Often partial replacement works well                               | Reference standard in aquafeeds                 | Reference standard in livestock feeds                     |
| Regulatory constraints       | Substrate restrictions; evolving standards                         | Established globally                            | Established globally                                      |
| Scalability                  | Growing fast; depends on automation + standards                    | Mature but resource-limited                     | Mature, large-scale agriculture                           |

BSFL-derived protein powders have also been tested in sports nutrition formulations, offering comparable digestibility to whey and soy isolates while providing additional fatty acids such as lauric acid with potential antimicrobial and metabolic benefits. When compared with other insect-based ingredients such as mealworm or cricket meal, BSFLM often provides a higher lipid fraction and favorable amino acid balance, making it a competitive alternative in the growing edible insect market (Meyer-Rochow *et al.*, 2021).

Acceptance of insect-based foods, however, remains culturally dependent. Studies across Belgium, Italy, China, Mexico and the United States have shown that while consumers acknowledge sustainability benefits, hesitancy persists due to neophobia and aesthetic barriers (Tzompa-Sosa *et al.*, 2023). To address this, BSFLM has been successfully integrated into processed forms (flour, powders) that are less visually identifiable as insect derived. In addition, BSFL-derived foods are currently regulated under the EU Novel Food Regulation (EU 2015/2283), requiring safety assessments that include allergenicity, microbiological hazards and heavy metal accumulation Tzompa-Sosa *et al.* (2023). Ongoing research continues to refine processing methods that minimize risks while enhancing nutritional and sensory quality.

Beyond nutritional composition, BSFLM provides functional health benefits when incorporated into feed or food products. In poultry and aquaculture, diets supplemented with BSFLM have been shown to enhance gut microbiota diversity and stimulate immune responses, attributed to antimicrobial peptides and medium-chain fatty acids such as lauric acid (Elhag *et al.*, 2017; Schiavone *et al.*, 2019). These compounds can reduce colonization by pathogenic bacteria, thereby lowering reliance on antibiotics. In human nutrition, BSFL protein has demonstrated high digestibility with a PDCAAS comparable to that of beef and chicken (Huis and Tomberlin, 2017). However, allergenic potential remains a consideration, as some insect proteins exhibit cross-reactivity with crustacean allergens (EFSA, 2015). Collectively, these findings suggest that BSFLM is not only a nutrient-dense ingredient but also a functional one with the capacity to improve health outcomes in both animal

and human systems. More broadly, edible insects are increasingly framed as an emerging food-processing sector, but large-scale adoption remains constrained by consumer perception, regulatory clarity and the need for standardized processing systems (Nitharwal *et al.*, 2022).

Despite its potential as a novel protein ingredient, several limitations currently constrain the expansion of BSFLM into mainstream human nutrition. First, food safety risks remain closely linked to rearing substrates and processing controls, particularly with respect to microbiological hazards and the possible accumulation of chemical contaminants such as heavy metals or pesticide residues, which require strict monitoring and regulatory oversight (EFSA, 2015; FAO, 2021). Second, allergenicity remains an important concern, as insect proteins may exhibit cross-reactivity with crustacean allergens, requiring clear labeling and further clinical validation before widespread adoption (EFSA, 2015). Third, nutritional composition and sensory outcomes can vary substantially across insect species, developmental stage, diet and processing methods, creating challenges for standardization in food-grade formulations (Meyer-Rochow *et al.*, 2021). Finally, consumer acceptance remains a persistent barrier in many regions, where neophobia and cultural resistance toward insect-based foods continue despite growing sustainability awareness; this suggests that product format, marketing and regulatory trust will strongly shape market feasibility (Nitharwal *et al.*, 2022; Tzompa-Sosa *et al.*, 2023; Huis and Tomberlin, 2017). Collectively, these limitations indicate that while BSFLM shows promise for human food applications, its scalability will depend on consistent safety assurance, standardized processing and improved consumer acceptance pathways.

### Waste management and circular economy

One of the most transformative applications of BSFL is in organic waste bioconversion. BSFL can process diverse waste streams-including food scraps, agricultural residues and animal manure-reducing waste mass by up to 50-80% within days (Diener *et al.*, 2011). The process diverts organic waste from landfills, reducing methane

**Table 3:** Typical feed substitution levels of BSFLM reported in feeding trials.

| Sector                   | Replacement target | Substitution level                | Outcome                                                   | References                                             |
|--------------------------|--------------------|-----------------------------------|-----------------------------------------------------------|--------------------------------------------------------|
| Aquaculture (fish)       | Fishmeal           | 25-50%                            | Often maintains growth and feed efficiency                | St-Hilaire <i>et al.</i> , 2007; Nguyen and Tran, 2025 |
| Aquaculture (catfish)    | Fishmeal           | 50%                               | Highest growth; lowest FCR; improved RBC/Hb/PCV           | Bordoloi <i>et al.</i> , 2025                          |
| Aquaculture (eel, loach) | Fishmeal           | Partial to moderate               | Maintains growth; acceptable meat quality                 | Nguyen <i>et al.</i> , 2025; Tran and Nguyen, 2025     |
| Poultry                  | Soybean meal       | 10-25%                            | Maintains growth; may improve carcass traits              | Schiavone <i>et al.</i> , 2019; Nguyen and Tran 2024   |
| Poultry (broiler)        | Soybean meal       | 25% (best), 35-50% less effective | 25% improved performance; higher levels reduced gains/FCR | Sampathkumar <i>et al.</i> , 2026                      |

emissions and environmental pollution (Parodi *et al.*, 2020). The frass generated during BSFL rearing contains nitrogen, phosphorus and potassium, making it suitable as an organic fertilizer (Meneguz *et al.*, 2018). Some studies also report that BSFL frass can promote plant growth and soil microbial activity (Salomon *et al.*, 2025; Gebremikael *et al.*, 2022). Integrating BSFL production into waste management systems supports a circular economy model, where low-value organic waste is transformed into high-value protein and fertilizer products (Smetana *et al.*, 2019). This approach has been successfully demonstrated at municipal and industrial scales in Europe, Asia and Africa (Smetana *et al.*, 2023).

Large-scale applications further highlight BSFL's systemic impact. A case study in Singapore found that BSFL bioconversion reduced food waste volumes by up to 65% while generating insect protein suitable for aquafeeds, illustrating its dual role in waste reduction and feed production (Ramzy *et al.*, 2025). Similarly, it was demonstrated that integrated BSFL waste management systems reduced methane emissions from landfills while producing nutrient-rich frass fertilizers that improved crop yields (Parodi *et al.*, 2020). Such results emphasize BSFLM's capacity to contribute to circular economy models by closing nutrient loops and replacing resource-intensive inputs in both feed and agriculture. When compared with traditional waste treatment pathways such as composting or anaerobic digestion, BSFL bioconversion achieves faster processing times and produces high-value outputs, underscoring its superior scalability (Halloran *et al.*, 2016).

### Safety considerations

The large-scale adoption of BSFLM for feed and food requires careful attention to safety, since risks can arise from both production substrates and processing methods.

The European food safety authority (EFSA) (EFSA 2015) and subsequent studies emphasize several potential hazards that must be managed to ensure consumer and animal health. While BSFLM presents significant opportunities as a sustainable feed and food ingredient, maintaining strict safety standards for substrates, processing and labeling is essential. Addressing these issues through harmonized international regulations will be crucial for scaling production and achieving consumer trust.

### Microbiological safety

If larvae are reared on improperly managed substrates, pathogens such as *Salmonella spp.* or *Escherichia coli* may persist and enter the food chain. However, thermal treatments such as blanching and oven-drying significantly reduce microbial loads and studies show that properly processed BSFLM can meet international microbiological safety standards (Schiavone *et al.*, 2019).

### Chemical contaminants

BSFL are known to bioaccumulate heavy metals, mycotoxins and pesticide residues depending on the rearing substrate (Purschke *et al.*, 2017). This risk underscores the importance of regulating substrate inputs, for example, the European Union currently prohibits catering waste and manure for BSFLM intended for feed or food (Lähteenmäki-Uutela *et al.*, 2017). Regular monitoring of cadmium, lead and arsenic levels is essential, as their accumulation can pose long-term health concerns.

### Process safety

Processing techniques play a critical role in ensuring BSFLM safety. Defatting, blanching and drying not only improve storage stability but also minimize microbial and chemical risks. In addition, feed-to-food safety protocols, such as hazard analysis and critical control point (HACCP) systems, are being adapted for insect-based production facilities (van Huis and Tomberlin, 2017).

### Prospects

The future of BSFLM production appears promising, driven by global demand for sustainable protein sources, growing pressure to reduce agricultural environmental footprints and advancements in insect-rearing technologies.

### Market potential and growth trends

Global demand for insect-based proteins is projected to grow rapidly, with estimates suggesting the market could exceed USD 4.1 billion by 2030 (FAO, 2021; Huis and Tomberlin, 2017). The BSF market alone is anticipated to rise rapidly over the next few years, with the global market value of \$128 million in 2019 is expected to increase to \$3.4 billion by 2030 (Siddiqui *et al.*, 2024). Asia and Europe are expected to be the primary growth regions, driven by aquaculture feed demand, pet food innovation and adoption

**Table 4:** Environmental benefits of BSFLM.

| Metric                  | Benefit                   | Interpretation                                                 | References                                                                              |
|-------------------------|---------------------------|----------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| GHG emissions           | ~30-40% reduction         | LCA outcomes depend on boundaries, substrate, scale and method | Smetana <i>et al.</i> , 2016; Smetana <i>et al.</i> , 2019; Parodi <i>et al.</i> , 2020 |
| Land use                | >70% reduction            | Stronger advantage vs soybean meal systems                     | Smetana <i>et al.</i> , 2016; Smetana <i>et al.</i> , 2019                              |
| Organic waste reduction | 50-80%                    | Rapid bioconversion within days                                | Diener <i>et al.</i> , 2009; Diener <i>et al.</i> , 2011                                |
| Landfill diversion      | Reduced methane potential | Depends on waste stream and infrastructure                     | Smetana <i>et al.</i> , 2019; Parodi <i>et al.</i> , 2020                               |

of insect-based ingredients in livestock diets. Increasing consumer awareness of sustainability, along with corporate commitments to reducing environmental impacts, will further boost industry adoption (Smetana *et al.*, 2016; 2023).

### Technological advancements

Recent innovations in automation, climate control and AI-assisted monitoring have enhanced production efficiency and scalability. Vertical farming systems and conveyor-based rearing allow year-round BSFL production with consistent quality (Parodi *et al.*, 2020). Moreover, advances in genetic selection and microbiome management could further improve feed conversion efficiency, growth rates and disease resistance (Gold *et al.*, 2020). In parallel, improvements in downstream processing-such as low-temperature drying, supercritical CO<sub>2</sub> oil extraction and functional protein isolation-are expanding the potential applications of BSFL-derived products in specialized animal diets and human nutrition (Sprangers *et al.*, 2017).

### Regulatory landscape

The regulatory environment for BSFL use in feed and food is evolving. In the European Union, BSFLM is authorized for use in aquaculture feeds (Regulation (EU) 2017/893) and more recently for poultry and pig feeds (Regulation (EU) 2021/1372). However, regulations on substrates for rearing remain strict, limiting the use of certain waste streams such as catering waste and manure for larvae intended for feed or food applications (EFSA, 2015). Expanding these regulations-while ensuring food and feed safety-will be crucial for scaling production. In Asia, countries like China, Vietnam and Singapore are rapidly developing standards for insect protein production, whereas in Africa, Kenya and South Africa have taken early steps to formalize the sector (Meyer-Rochow *et al.*, 2021; Lähtenmäki-Uutela *et al.*, 2017; Halloran *et al.*, 2016). Harmonization of regulations across regions could unlock international trade potential.

### Environmental and social impact

BSFL production can contribute to climate change mitigation by reducing greenhouse gas emissions associated with organic waste disposal and substituting resource-intensive protein sources like fishmeal and soy (Smetana *et al.*, 2019). Socially, BSFL farming offers income-generation opportunities in rural and peri-urban communities, especially in developing countries, where it can be integrated into smallholder farming systems (Makkar *et al.*, 2014). Scaling BSFLM production could directly contribute to several SDGs, including SDG 8 (Decent Work and Economic Growth) through rural job creation, SDG 9 (Industry, Innovation and Infrastructure) via the development of novel bioconversion technologies and SDG 15 (Life on Land) by reducing pressure on land resources (Akwa *et al.*, 2025; Sarangi *et al.*, 2024; Ramzy *et al.*, 2025). Integration of BSFL into waste management systems supports SDG 12 targets by promoting resource efficiency and closing nutrient loops

in agricultural value chains (Akwa *et al.*, 2025; Hsu *et al.*, 2025). Key environmental benefits associated with BSFLM production and substitution pathways are summarized in Table 4, including reported reductions in greenhouse gas emissions, land use and organic waste mass.

### Research needs

Future research on BSFLM should shift from broad opportunity mapping toward addressing a set of priority gaps that currently limit large-scale adoption. First, the most immediate constraint is safety assurance under variable substrate conditions, particularly the need to optimize rearing substrates while minimizing contaminant risks such as heavy metals, mycotoxins and microbial hazards (Purschke *et al.*, 2017; EFSA, 2015). Second, there remains a major gap in robust, comparable environmental evidence, as life cycle assessment outcomes differ substantially across production scales, energy inputs, geographic contexts and methodological choices; therefore, harmonized LCAs are required to generate reliable benchmarks and identify improvement levers (Smetana, Schmitt and Mathys, 2019). Third, production consistency and cost-efficiency remain unresolved bottlenecks, requiring selective breeding and process optimization to stabilize yield, nutritional composition and resilience across industrial conditions (Gold *et al.*, 2020). Fourth, stronger evidence is needed on the economic and sustainability value of by-product valorization, including frass as a biofertilizer and chitin-based bioproducts, as these co-products may determine commercial viability in circular economy systems (Xiong *et al.*, 2023; Mirwandhono *et al.*, 2022; Salomon *et al.*, 2025). Finally, research into consumer acceptance, particularly in regions unfamiliar with entomophagy, will be critical for expanding BSFL-derived products into human food markets (Huis and Tomberlin, 2017). Addressing these research gaps will be vital to integrating BSFLM more fully into global feed and food systems, thereby supporting the transition toward a circular bioeconomy.

### Advantages and limitations

The adoption of BSFLM offers notable sustainability, nutritional and socio-economic benefits, but also faces several challenges that must be addressed for its large-scale integration into global food and feed systems. BSFLM is rich in protein (40-45% crude protein) and lipids (25-35%), with an amino acid profile containing lysine and methionine-nutrients often deficient in plant-based feeds (Barragan-Fonseca *et al.*, 2017). Feeding trials in aquaculture and poultry demonstrate that BSFLM can replace 25-50% of fishmeal or soybean meal without compromising growth performance or meat quality (St-Hilaire *et al.*, 2007; Schiavone *et al.*, 2019; Nguyen and Tran, 2025). Its antimicrobial peptides and lauric acid also enhance animal gut health and immunity (Elhag *et al.*, 2017), reducing reliance on antibiotics. Environmentally, BSFL production requires up to 70% less land and water compared with soybean cultivation and life cycle assessments

report greenhouse gas emissions reductions of 30-40% when substituting fishmeal with insect protein (Smetana, Schmitt and Mathys 2019; Halloran *et al.*, 2016). Moreover, the larvae can recycle 50-80% of organic waste into high-value biomass, supporting circular economy models and contributing to SDGs related to responsible consumption and climate action (Diener *et al.*, 2009; Ramzy *et al.*, 2025). Socially, BSFL farming creates livelihood opportunities in rural and peri-urban communities, particularly in developing countries, by providing an accessible source of animal feed and organic fertilizer (Meyer-Rochow *et al.*, 2021).

Despite these advantages, significant challenges hinder the mainstream adoption of BSFLM. Production costs remain relatively high compared to conventional protein meals, largely due to processing, drying and oil extraction steps (Siddiqui *et al.*, 2024). Nutritional composition can vary widely depending on rearing substrates, leading to inconsistencies in protein and lipid content (Sprangers *et al.*, 2017). Safety concerns also remain: larvae may accumulate heavy metals, pesticides, or mycotoxins from contaminated substrates, necessitating strict control and regulation (Purschke *et al.*, 2017; EFSA, 2015). Consumer acceptance of insect-based foods is limited in many regions due to cultural barriers, with surveys indicating persistent neophobia despite growing awareness of sustainability benefits (Tzompa-Sosa *et al.*, 2023). Moreover, regulatory restrictions such as the European Union's prohibition of catering waste as a rearing substrate, constrain the scalability of insect farming for feed and food (Lähtenmäki-Uutela *et al.*, 2017). Finally, large-scale industrial production requires further advances in automation, selective breeding and biosecurity to ensure cost-efficiency and consistent quality (Gold *et al.*, 2020). Balancing these advantages and limitations highlights the need for continued research, supportive policy frameworks and consumer education to position BSFLM as a viable, sustainable alternative to conventional protein sources.

## CONCLUSION

BSFLM is increasingly positioned as a scalable alternative protein ingredient with relevance beyond feed substitution, particularly in circular economy systems that connect organic waste conversion, protein production and by-product valorization. This review contributes by synthesizing BSFLM through a system-level lens, highlighting how nutritional consistency, safety assurance and environmental performance are jointly shaped by substrate choice, processing intensity and production scale rather than by ingredient composition alone. The review further emphasizes that large-scale adoption will depend on harmonized safety standards, comparable environmental benchmarking and industrial optimization to ensure reliable quality across production contexts. Addressing these priority gaps will be essential for BSFLM to transition from a promising innovation to a mainstream ingredient in global feed and food value chains.

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## Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

## Informed consent

Not applicable.

## Conflict of interest

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