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WASTE TO WEALTH: ORGANIC WASTE RECYCLING AND VALORIZATION THROUGH BLACK SOLDIER FLY (*HERMETIA ILLUCENS* L.) BIOCONVERSION

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ABSTRACT
The rapid increase in organic waste generation driven by population growth, urbanization, and intensification of agri-food systems represents a critical global environmental challenge. Current estimates indicate that approximately 2.0 - 2.3 billion tonnes of municipal solid waste is generated annually worldwide, with 45–55% comprising biodegradable organic matter. Conventional disposal practices such as landfilling and incineration are associated with significant greenhouse gas emissions, nutrient losses, and land-use constraints. Black soldier fly (*Hermetia illucens* L.) bioconversion has emerged as an efficient and environmentally sustainable waste-to-wealth strategy. Experimental studies demonstrate that black soldier fly larvae (BSFL) can reduce organic waste mass by 50–80% within 10–14 days, depending on substrate type, larval density, and rearing conditions. During this process, larvae convert waste nutrients into high-value biomass containing 35–45% crude protein and 25–35% lipids on a dry matter basis while the residual frass retains significant agronomic value. This review provides a comprehensive and quantitative synthesis on black soldier fly-mediated organic waste bioconversion, encompassing larval biology, waste degradation mechanisms, system performance indicators, and substrate-dependent efficiencies, along with industrial valorization pathways, environmental impacts assessed through life cycle analysis, and economic feasibility. It further presents an integrated perspective on the role of BSF bioconversion in advancing circular bioeconomy systems and identifies key research priorities for its sustainable and scalable deployment.

KEYWORDS: Black soldier fly; *Hermetia illucens*; organic waste recycling; insect bioconversion; waste valorization; circular bioeconomy; frass fertilizer

INTRODUCTION
Rapid population growth, urbanization, and shifting consumption patterns have driven global municipal solid waste past 2 billion tonnes annually, with organic fractions comprising nearly half of this total (1–3). Conventional disposal methods present significant drawbacks: landfills are major sources of global anthropogenic methane emissions (4), incineration risks air pollution and nutrient loss (5), and traditional biological treatments like composting and anaerobic digestion suffer from high land, time, or capital constraints (6–8). To address these challenges, insect-based bioconversion using the black soldier fly (*Hermetia illucens* L., BSFL) has emerged as a promising circular-bioeconomy strategy (9–11). BSFL efficiently consume diverse organic streams such as food waste, manure, and agricultural residues converting them into valuable biomass (12–15). However, high variability in waste reduction across studies, driven by differing substrate compositions and operational parameters, complicates direct comparisons (16–18). Furthermore, technical, regulatory, biosafety, and socioeconomic hurdles continue to limit large-scale industrial adoption (19–26). This work provides a comprehensive evaluation of BSF technology by comparing organic-waste substrates, detailing larval gut microbiome functions and biochemical degradation pathways, examining chitin and chitosan recovery, assessing frass for agricultural applications, and contrasting the environmental benefits of BSF farming with traditional waste management practices (27–29).

2. BIOLOGY AND ECOLOGY OF THE BLACK SOLDIER FLY (*HERMETIA ILLUCENS*)
The BSF (*Hermetia illucens* L.) belongs to the family Stratiomyidae and is indigenous to tropical and subtropical regions, although it has successfully adapted to temperate environments through controlled rearing systems (12, 30). Its biological characteristics, particularly during the larval stage, support its capacity for organic-waste bioconversion (31, 32). Adult females lay 400–900 eggs in clusters near decomposing organic substrates, ensuring immediate access to food for emerging larvae (30, 33). Egg incubation lasts 3–4 days under optimal temperature and humidity conditions (34). The larval stage, which spans approximately 12–18 days, is characterized by intensive feeding and rapid biomass accumulation (35). During larval development, body mass may increase by many folds, supported by feed conversion ratios ranging from 1.5 to 2.2, depending on substrate quality and rearing density (16, 36). Larval digestive capacity is facilitated by a complex enzymatic system, including proteases, lipases, and carbohydrases, which enable efficient degradation of diverse

organic compounds (37, 38). Before pupation, fifth-instar larvae migrate from the feeding substrate to dry, sheltered locations to initiate pupation. The exoskeleton darkens, and the pupa develops within the hardened larval cuticle. Pupation requires about two weeks (39). The gut microbiome of BSFL further enhances substrate decomposition and nutrient assimilation (40). Studies have shown that gut-associated microbial communities contribute to the breakdown of recalcitrant organic matter and may suppress pathogenic microorganisms through competitive exclusion and antimicrobial activity (41, 42). Ecologically, *H. illucens* is considered a non-pest species. Adult flies lack functional mouthparts and do not feed, eliminating the risk of pathogen transmission associated with synanthropic flies (43). Furthermore, BSFL can reduce populations of pest flies by competing for oviposition sites and larval substrates (44). Larval performance is strongly influenced by environmental conditions. Optimal growth and survival are generally observed at temperatures between 27 and 33°C, substrate moisture levels of 60–70%, and adequate aeration, with survival rates frequently exceeding 90% under controlled conditions (45). The development life cycle of *Hermetia illucens* is illustrated in Figure 1.

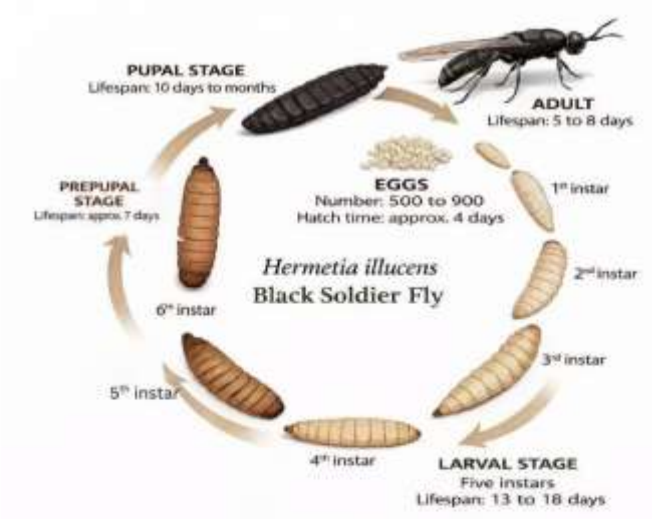

Figure 1. Life cycle of the black soldier fly, *Hermetia illucens*

3. TYPES OF ORGANIC WASTE STREAMS UTILIZED IN BLACK SOLDIER FLY BIOCONVERSION

One of the most important attributes of BSF *(Hermetia illucens)* bioconversion is the larvae's capacity to utilize a wide spectrum of organic waste streams (46). This flexibility allows BSF systems to be applied across agricultural, industrial, and municipal waste management contexts, enhancing their relevance to circular bioeconomy frameworks (47, 48).

3.1 Food Waste and Kitchen Residues

Food waste represents one of the most abundant and nutrient-rich organic waste streams globally. It is estimated that approximately 1.3 billion tonnes of food waste is generated annually, accounting for nearly one-third of all food produced for human consumption (1). Owing to their high carbohydrate, protein, and lipid contents, food-waste substrates generally support relatively high waste reduction and larval growth. Experimental studies consistently report high waste reduction efficiencies when BSFL are reared on food waste (49). (13) observed 55–70% reduction in fresh weight of household food waste within 12–14 days, while (16) reported waste mass reductions of up to 75% under optimized moisture and feeding regimes. Larval biomass yields on food waste typically range from 150 to 220 g per kg of dry substrate, with feed conversion ratios between 1.6 and 2.0 (50). However, food waste composition can vary considerably depending on dietary patterns and processing methods (51). High salt content (>2%) and excessive fat levels have been reported to negatively affect larval survival and growth (52). Pre-treatment methods such as grinding, dilution, or co-feeding with fibrous materials are often employed to stabilize substrate quality and improve bioconversion efficiency.

3.2 Agricultural Residues and Crop-Based Wastes

Agricultural activities generate large volumes of organic residues, including crop residues, vegetable trimmings, fruit pulp, and post-harvest losses. Globally, agricultural residues account for several billion tonnes of biomass annually, much of which remains underutilized. Compared to food waste, agricultural residues often contain higher proportions of structural carbohydrates such as cellulose and lignin, which can limit digestibility (53). Studies have shown that BSFL reared exclusively on fibrous residues exhibit lower growth rates and biomass yields. (54) reported larval yields of 80–120 g per kg dry substrate on vegetable residues, compared to >180 g/kg on food waste. Combining agricultural residues with nutrient-rich substrates such as food waste or agro-industrial by-products has been shown to improve larval performance significantly (55). (17) demonstrated that co-feeding vegetable waste with brewery by-products increased waste reduction efficiency from 48% to over 65% and improved larval protein content by approximately 6–8 percentage points.

3.3 Livestock Manure

Livestock manure represents a major environmental concern due to detestable odour generation, pathogen presence, and nutrient leaching. BSFL have demonstrated strong potential for manure management, particularly in poultry and swine production systems (56) (14). Earlier studies reported that BSFL could reduce poultry manure mass by 50–60% within 7–

10 days, while simultaneously reducing moisture content and odour intensity(56). BSFL can effectively transform poultry litter, a nutrient-rich but environmentally problematic waste, into two value-added products: frass with fertilizer potential and insect biomass rich in protein and fats (57). (14) observed that larval treatment reduced populations of Escherichia coli and Salmonella by more than 90%, highlighting the hygienic benefits of BSF bioconversion. Larval biomass yields on manure-based substrates are generally lower than those obtained on food waste, typically ranging from 90 to 140 g per kg dry substrate, with protein contents of 32–38% (54). Nevertheless, manure stabilization and pathogen reduction indicate that BSF systems may have practical value in livestock-waste management.

3.4 Agro-industrial By-products

Agro-industrial processing generates substantial quantities of organic by-products such as brewery spent grains, oilseed cakes, fruit pomace, sugar industry residues, and distillery waste (58). These by-products are often nutrient-rich and relatively homogeneous, making them suitable feedstocks for BSF. (15) reported that BSFL reared on brewery spent grains achieved waste reduction efficiencies of 60–70%, with larval biomass yields exceeding 180 g per kg dry substrate. Similarly, BSFL reared on fruit-processing waste exhibited protein contents of 38–44% and lipid contents of 28–32%, depending on substrate composition (59) .The integration of BSF systems into agro-industrial value chains may reduce waste-disposal requirements while generating co-products for feed and agriculture.

3.5 Municipal Organic Waste

Municipal solid waste contains a substantial organic fraction that can be targeted for BSF bioconversion, particularly in regions with effective waste segregation practices (60). (13) demonstrated that BSFL could reduce the organic fraction of municipal waste by 50–65% within two weeks, provided that contaminants such as plastics and metals were removed. However, municipal waste streams pose challenges related to heterogeneity and contamination. Studies have reported potential accumulation of heavy metals such as cadmium and lead in larval biomass when BSFL are reared on contaminated substrates. Consequently, strict feedstock control and pre-sorting are essential to ensure biosafety and regulatory compliance. A comparative analysis of waste reduction efficiency and protein yield across different substrates is presented in Figure 2, highlighting the trade-offs between waste-reduction performance and larval biomass quality.

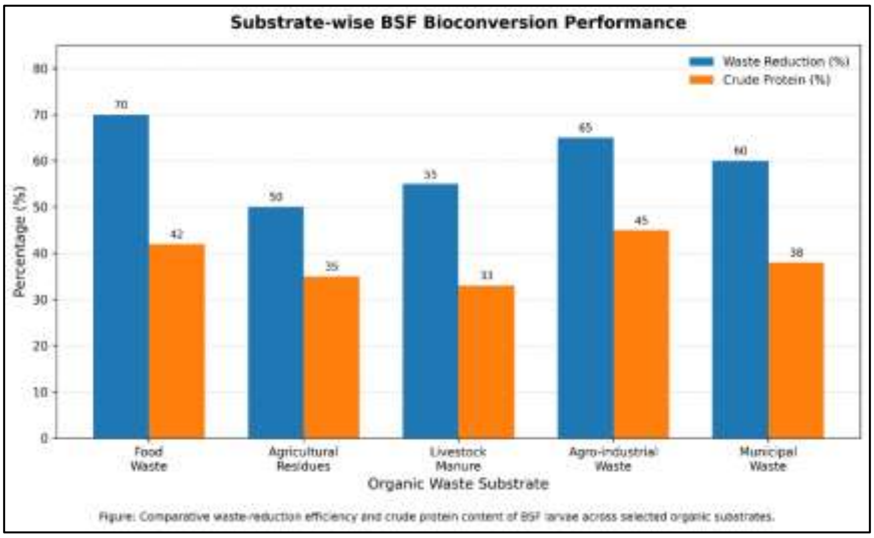

Figure 2. Waste-reduction efficiency and crude protein content of black soldier fly larvae reared on different organic substrates

In the studies summarized, food and agro-industrial wastes generally showed comparatively higher waste-reduction and protein-content values; however, performance depended on substrate composition and experimental conditions. The nutritional composition of black soldier fly larvae varies significantly depending on the type of substrate used, particularly in terms of crude protein and lipid content, as summarized in Table 1.

Substrates rich in balanced protein and digestible carbohydrates (e.g., chicken feed and mixed agro-industrial residues) enhance both protein synthesis and lipid accumulation, whereas lignocellulosic or low-nutrient substrates such as fruit and manure-based wastes result in reduced lipid deposition and moderate protein levels (61).

Table 1. Substrate-dependent variation in the crude protein and lipid contents of black soldier fly larvae.

Feeding Substrate	Crude Protein (%)	Crude Lipid (%)	Reference
High-Efficiency Substrate			
Poultry waste	45.55	28.40	(62)
Soybean curd residue mix	44.50	35.00	(63)
Mixed agro-industrial waste	44.0	31.00	(64)
Food waste	42.1	34.8	(50)
Vegetable waste	39.3	29.5	(54)

Mixed food waste	43.5	33.2	(17)
Industrial & Municipal By-product			
Brewery spent grains	41.8	31.6	(65)
Sewage sludge	40.2	26.5	(16)
Cassava pulp	42.80	15.00	(66)
Sludge + chicken feed (75:25)	41.79	30.38	(62)
Manure & Fibrous Waste			
Poultry manure	33.8	27.2	(62)
Pig manure	35.5	28.0	(67)
Cow manure	38.20	21.50	(62)
Fruit waste	36.7	21.9	(68)
Pineapple peel	53.60	7.60	(66)

4. MECHANISMS OF ORGANIC-WASTE DECOMPOSITION DURING BSFL BIOCONVERSION

The decomposition of organic waste by *Hermetia illucens* larvae represents a highly coordinated biological sequence, integrating mechanical fragmentation, multi-stage enzymatic hydrolysis, and complex microbial successions. Unlike conventional composting, which relies primarily on slow aerobic degradation, BSF-mediated bioconversion is characterized by rapid processing kinetics, resulting in accelerated decomposition and nutrient transformation (69). As illustrated in Figure 3, larval-mediated decomposition is a multistep process involving the physical breakdown of substrates, enzymatic hydrolysis, and microbiome-driven pathogen suppression.

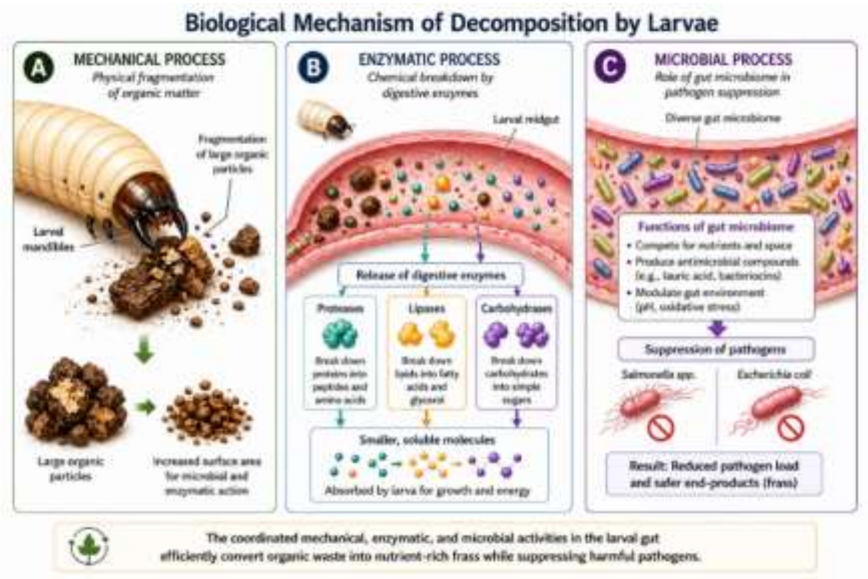

Figure 3. Biological mechanisms of organic-waste decomposition by black soldier fly larvae

(A) Mechanical process: Larval mandibles fragment large organic particles, increasing surface area for subsequent degradation. (B) Enzymatic process: Digestive enzymes, including proteases, lipases, and carbohydrases, break down complex macromolecules into simpler, absorbable forms. (C) Microbial process: The gut microbiome facilitates nutrient conversion and suppresses pathogenic microorganisms such as *Salmonella* spp. and *Escherichia coli*, resulting in safer, nutrient-rich end products (frass).

BSF larvae decompose organic waste via integrated physical, enzymatic, microbial, and biochemical mechanisms. Sclerotized mandibles fragment substrate, increasing surface area for microbial colonization, while larval burrowing enhances aeration, prevents anaerobic zones, and regulates moisture (13, 16). Endogenous and microbial proteases, lipases, and carbohydrases hydrolyze proteins, lipids, and carbohydrates, with enzyme activity adapting to substrate type and functioning optimally under the alkaline gut (37, 40, 70). The gut microbiota predominantly Proteobacteria, Firmicutes, and Bacteroidetes augments digestion by secreting extracellular hydrolases that degrade lignocellulose and protein matrices, and by fermenting metabolites into short-chain fatty acids (SCFAs) that support larval growth; taxa such as Enterococcus and Providencia mediate nitrogen recycling and nutrient partitioning (41, 71-73). Concurrently, gut pH fluctuations, antimicrobial peptides (e.g., defensins, cecropins), and microbial competitive exclusion hygiene the substrate, reducing pathogens such as *Salmonella* spp., *Escherichia* coli, and *Staphylococcus aureus* during BSF processing (74-77). Ingested organic matter is partitioned among larval biomass, metabolic losses, and frass, typically evaluated using feed conversion ratio (FCR), bioconversion rate (BCR), and waste reduction index (WRI). BSFL convert 15–25% of substrate into biomass (20–25% protein, 15–20% lipid conversion efficiency), with the remainder lost as CO_2 or retained in nutrient-rich (N, P, K) frass (78). This frass undergoes further biochemical maturationreducing VOCs and pathogen load while promoting humic-like and fulvic acid formation enhancing its stability, agronomic value, and carbon sequestration potential, often within a shorter processing period than conventional composting (79). The mechanisms underlying organic waste decomposition in BSF larvae are summarized in Figure 4. BSF-mediated treatment may require shorter active processing period than conventional composting, although nutrient retention depends on feedstock, process conditions, and assessment methods.

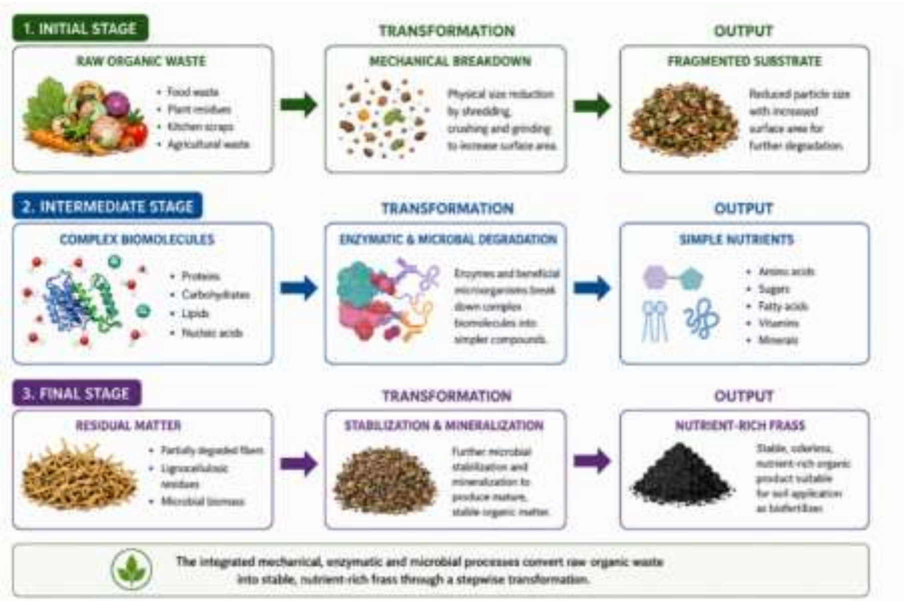

Figure 4. Transformation of organic waste during black soldier fly larval bioconversion.

5. PROCESS OPTIMIZATION AND PERFORMANCE INDICATORS IN BSFL BIOCONVERSION

The performance of BSF bioconversion is strongly influenced by biological, environmental, and operational parameters. Optimization of these parameters is essential for maximizing waste reduction efficiency, larval biomass yield, and nutritional quality while ensuring system stability and scalability (28, 80).

5.1 Substrate Quality and Nutrient Balance

Substrate composition remains a primary determinant of larval performance. Studies generally indicate that balanced protein-to-energy ratios can improve larval growth and feed-conversion performance (81). Specifically, crude protein levels between 14% and 20% are associated with optimal biomass yields, whereas protein-deficient or highly fibrous agricultural residues significantly impede growth rates (13). Reported feed conversion ratio (FCR) values for BSFL typically range from 1.5 to 2.2, depending on substrate type and feeding regime (16, 36). Nutrient-rich food waste and agro-industrial by-products generally produce lower FCR values (higher efficiency) compared to lignocellulosic fibrous agricultural residues.

5.2 Nutritional Composition of BSF Larvae

Across different studies, the crude protein and lipid composition of BSF larvae varied substantially according to substrate type, larval developmental stage, analytical method, and whether the biomass was evaluated as whole, full-fat, partially defatted, or fully defatted meal (50, 54, 82). BSFL contain all essential amino acids required for animal nutrition, with lysine and methionine levels comparable to those found in fishmeal (21, 83). The fatty acid profile is frequently characterized by a substantial proportion of lauric acid, although its concentration varies with diet composition and developmental stage (50, 68, 84). Figure 5 presents the nutritional composition of black soldier fly larvae.

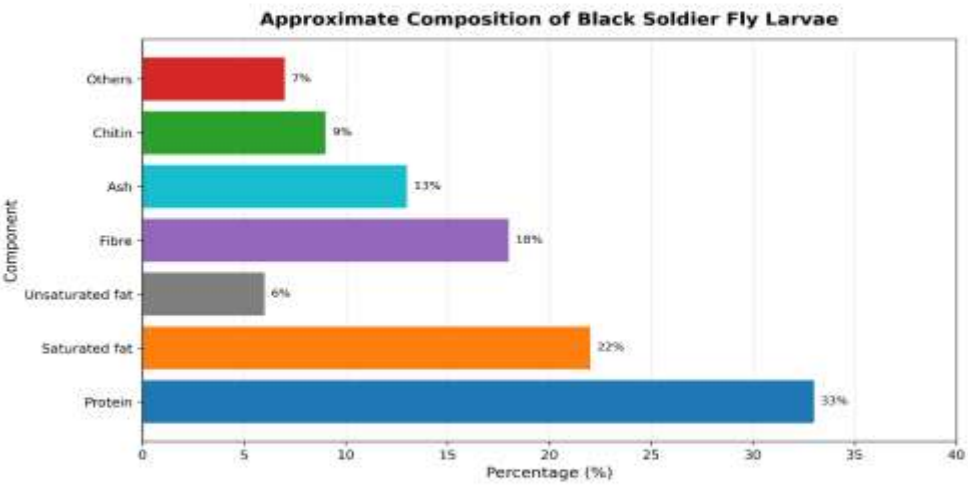

Figure 5. Nutritional composition of black soldier fly larvae, modified from Meneguz *et al.* (2018).

5.3 Feeding Rate and Feeding Regime

The feeding rate directly influences larval survival and metabolic heat production. Optimal rates are generally between 100–150 mg of substrate per larva per day. Exceeding these levels can lead to substrate accumulation and subsequent anaerobic conditions, which can negatively affect larval performance. While batch feeding systems are common due to their operational simplicity, continuous feeding regimes are increasingly preferred for industrial scaling (85). Continuous systems maintain a steady nutrient supply and have been shown to improve waste reduction efficiency by 10–15% compared to batch systems (86).

5.4 Environmental Parameters: Temperature, Moisture, and Aeration

Environmental parameters exert a strong influence on BSFL metabolism and survival (87). Optimal larval growth consistently observed within a temperature range of 27–33°C, with growth rates declining sharply outside the 20–37°C range. Substrate moisture content between 60% and 70% is generally considered optimal (88). Excessive moisture above 75% can restrict oxygen diffusion and larval mobility, whereas moisture levels below 50% may limit substrate ingestion and larval growth. Consequently, adequate aeration is essential not only for oxygen supply but also for regulating metabolic heat and moisture loss.

5.5 Larval Density and Harvest Timing

Larval stocking density significantly affects system performance. Optimal densities typically range from 5,000–10,000 larvae per kg of substrate, balancing waste reduction efficiency and individual larval weight (36). Excessively high densities may accelerate waste degradation but often result in smaller larvae due to increased competition. Furthermore, the timing of the harvest influences nutritional composition. Larvae harvested at the late fifth instar or early prepupal stage exhibit maximum lipid accumulation, with lipid contents increasing by 5–10% compared to earlier stages (50). This stage is therefore preferred for applications targeting lipid extraction or bioenergy production.

5.6 Performance Indicators and System Evaluation

Several indicators are used to evaluate BSF bioconversion, including waste reduction, waste reduction index, larval biomass yield, feed conversion ratio, survival, development time, nitrogen recovery, and carbon conversion efficiency. Reported values differ substantially among studies because of variations in substrate composition, larval age, feeding rate, stocking density, moisture content, treatment duration, and wet- or dry-matter calculations (13, 18). Therefore, these indicators should be interpreted as study-specific outcomes rather than universal performance benchmarks. Standardized equations, complete dry-matter mass balances, and transparent reporting are required for meaningful cross-study comparison (28, 89).

5.7 Bioconversion Performance Metrics

The bioconversion performance of *Hermetia illucens* larvae across diverse organic substrates is summarized in Table 2.

Table 2. Bioconversion performance of *Hermetia illucens* larvae on different organic substrates.

Substrate type	Waste Reduction (WR %)	Waste Reduction Index (WRI)	Larval biomass yield (g/kg substrate)	Feed Conversion Ratio (FCR)	Larval survival (%)	Processing time (days)	Key observations	References
Food waste / kitchen waste	60–80	3.5–5.0	180–220	1.5–2.0	90–95	10–14	Highly suitable substrate; rapid larval growth	(13, 16)
Fruit and vegetable waste	55–70	3.0–4.2	150–200	1.8–2.3	85–92	10–14	High moisture may require mixing with dry material	(78)
Livestock manure	40–60	2.0–3.0	100–150	2.2–2.8	80–90	10–15	Lower nutrient availability compared with food waste	(30)
Agro-industrial by-products	50–75	3.2–4.5	160–210	1.7–2.2	85–93	10–14	Performance depends on nutrient composition	(12)
Municipal organic waste (segregated)	50–65	2.5–3.8	130–180	2.0–2.5	80–90	12–15	Requires proper pre-sorting to avoid contaminants	(60)

6. INDUSTRIAL AND BIOREFINERY APPLICATIONS OF BSF BIOMASS

BSF larval biomass can be processed into protein meal, lipids, biofuels, chitin, chitosan, antimicrobial compounds, and other industrial products (90-92). Product quality and suitability depend on the rearing substrate, developmental stage, processing method, safety status, and intended application (21). The principal valorization pathways is presented in Figure 6 and discussed in the following subsections.

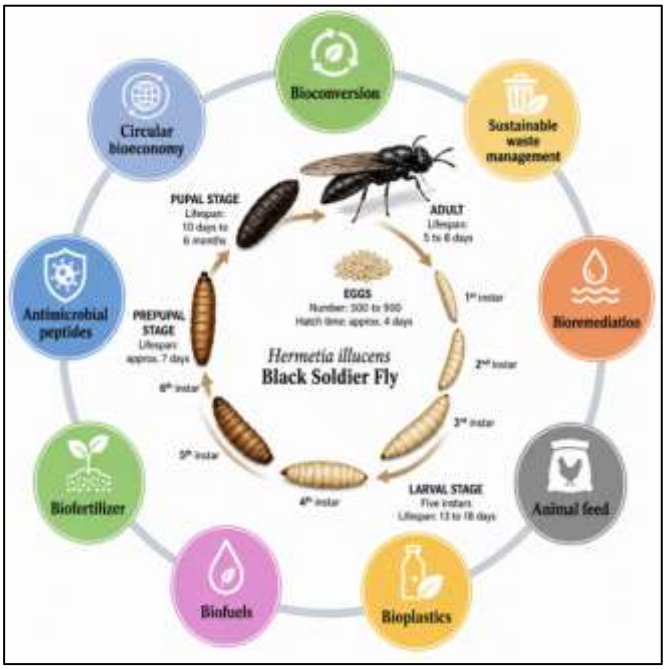

Figure 6. Development stages of (*Hermetia illucens)* and multifunctional role of BSF larvae in waste valorization and industrial biotechnology.

BSF larval biomass yields valuable protein and lipid fractions supporting dual applications in animal nutrition and bioenergy. The protein fraction, with a well-balanced amino acid profile, serves as a potential alternative to fishmeal and soybean meal in aquaculture, poultry, and livestock diets, while the lipid fraction physicochemically comparable to plant-based oils can be converted into biodiesel and other biofuels (93, 94).Defatting increases measured protein concentration in BSF meal by removing lipids, though final protein and residual lipid contents depend on biomass composition and extraction technology, supporting integration of BSF bioconversion into biorefinery systems.

In poultry and swine, BSF meal can replace 25–50% of soybean meal or 30–100% of fishmeal without adverse effects on growth, feed intake, or feed conversion efficiency (22). Broilers fed 10–15% BSF meal showed weight gain and feed conversion ratios comparable to conventional diets, with improved gut microbial balance (95) and similar results have been observed in piglets without negative impacts on health or productivity (96). Aquaculture represents one of the most promising markets for BSF-derived protein (97) BSF meal can replace 50–100% of fishmeal in tilapia, carp, and salmonid diets without significant reductions in growth or survival (98) and 75% fishmeal replacement in tilapia achieved comparable growth performance while reducing feed costs by 15–20% (99, 100).

Efficient bioconversion of organic waste into lipid-rich biomass also enables downstream biodiesel production with favourable fuel properties (93), positioning BSF-based systems as an alternative to conventional biofuel feedstocks (101) and supporting circular bioeconomy objectives through lower feed costs and reduced waste-disposal burdens. Commercial feasibility, however, depends on lipid yield, extraction efficiency, fuel quality, and production cost, requiring further techno-economic and life-cycle assessment (26, 102, 103)

Additionally, BSF exoskeletons offer a promising alternative chitin source for conversion into chitosan, used in agriculture, biomedicine, and wastewater treatment. Insect-derived chitin has lower mineral content and reduced dependence on marine resources compared to crustacean-derived chitin (48), and the resulting chitosan exhibits comparable biodegradability, biocompatibility, and antimicrobial activity for use in plant protection, drug delivery, and environmental remediation (104). Chitin content in BSF larvae typically ranges from 5–10% of dry weight depending on developmental stage and processing, underscoring its potential as a sustainable biopolymer within integrated biorefinery systems.

6.6 Biofertilizer (frass) applications

Black soldier fly (BSF) frass, the residual by-product of larval bioconversion, is increasingly recognized as a valuable organic fertilizer with strong agronomic potential. It contains a balanced composition of essential nutrients, typically ranging from 2–5% nitrogen, 1–3% phosphorus, and 1–2% potassium, along with organic matter and trace elements that contribute to soil fertility enhancement (79, 105). Application of BSF frass has been shown to increase crop yields and nutrient uptake by improving soil structure and microbial biomass. The presence of residual organic carbon further supports soil water retention and contributes to long-term soil health. However, its composition can vary depending on larval feed substrate and processing conditions, highlighting the need for standardization to ensure consistent performance under field conditions (106).

Figure 7. Circular-bioeconomy model for sustainable organic-waste valorization through black soldier fly bioconversion.

Figure 7 illustrates the integrated circular-bioeconomy approach to black soldier fly-based waste valorization. The major BSF-derived product streams differ in source material, application potential, safety requirements, technological maturity, and research needs.

7. FRASS FERTILIZER: COMPOSITION, AGRONOMIC VALUE, AND SOIL HEALTH IMPACTS

In addition to larval biomass, BSF bioconversion produces a substantial quantity of residual material known as frass (29). BSF frass consists of larval excreta, unconsumed substrate, shed exoskeletons, and microbial biomass .Increasing attention has been directed toward frass as a biofertilizer and soil amendment, contributing to nutrient recycling and sustainable agriculture.

The nutrient composition of BSF frass varies with substrate type and processing conditions but generally exhibits favourable characteristics for agronomic application (107). (105)) reported that nitrogen (N) contents typically range from 1.5 to 4.2%, phosphorus (P2O5) from 0.5 to 2.1%, and potassium (K2O) from 0.8 to 3.5% on a dry-matter basis. BSF frass also contains appreciable levels of organic carbon, with C:N ratios commonly between 10:1 and 18:1, which is conducive to microbial activity and nutrient mineralization in soils. Additionally, chitin and chitosan residues originating from larval exuviae are present at concentrations of approximately 2–6%, contributing to plant defence stimulation and disease suppression.

7.2 Effects on Soil Properties and Microbial Activity

Application of BSF frass has been shown to improve soil physical and biological properties, field and pot experiments demonstrate increases in soil organic matter by 8–15% and microbial biomass carbon by 10–25% following frass application at rates of 2–5 t ha^{-1}(108). Soils amended with BSF frass exhibited significantly higher enzymatic activities, including dehydrogenase and phosphatase activities, indicating enhanced microbial metabolic function. These improvements are comparable to or exceed those observed with traditional organic amendments such as compost and farmyard manure.

7.3 Crop Growth and Yield Responses

Several studies have documented positive crop responses to BSF frass application. (79) observed yield increases of 20–35% in maize and vegetables compared to unfertilized controls, and yields comparable to those achieved with synthetic NPK fertilizers at equivalent nitrogen rates. In horticultural crops, frass application improved root development and nutrient-use efficiency, particularly nitrogen and phosphorus. Furthermore, reduced incidence of soil-borne diseases has been reported, which has been attributed to chitin-induced systemic resistance and shifts in rhizosphere microbial communities (105).

7.4 Safety, Maturity, and Regulatory Aspects

BSF frass should not automatically be considered a mature or ready-to-use fertilizer because it may contain undegraded substrate, ammonium, soluble salts, pathogens, and unstable organic. Its maturity should be evaluated using pH, electrical conductivity, carbon-to-nitrogen ratio, nutrient composition, biological stability, and seed-germination response (106). Curing, composting, drying, or heat treatment may be required before agricultural application. Heavy metals may remain in the frass or accumulate in larvae when contaminated substrates are used (109). Pesticides, antibiotics, veterinary medicines, microplastics, and other contaminants may also be transferred from the original feedstock (110). Therefore, substrate traceability, contaminant testing, pathogen monitoring, and compliance with fertilizer regulations are essential.

8. ENVIRONMENTAL IMPACTS AND LIFE-CYCLE ASSESSMENT OF BSF SYSTEMS

One of the primary drivers for adopting BSF bioconversion is its potential to reduce the environmental footprint of organic waste management (97, 111). Life cycle assessment (LCA) studies provide quantitative evidence that BSF systems can reduce environmental impacts compared with conventional waste treatment options such as landfilling, composting, and anaerobic digestion (23).

8.1 Greenhouse Gas Emissions

LCA studies consistently demonstrate that BSF bioconversion significantly reduces greenhouse gas (GHG) emissions(112). BSF treatment of food waste resulted in 30–60% lower CO_2-equivalent emissions compared to landfilling and 20–35% lower emissions compared to composting. Methane emissions, a major contributor to the climate impacts of anaerobic waste management systems, may be reduced in BSF systems due to the aerobic nature of larval feeding (113). Methane emissions of less than 0.5 kg CO_2-equivalent per tonne of waste, compared to >50 kg CO_2-equivalent in unmanaged landfill scenarios(114).

8.2 Environmental Benefits of BSF Farming over Landfilling

Compared with landfilling, BSF farming provides a more resource-oriented pathway for managing suitable biodegradable organic wastes. Landfilling commonly results in methane generation, leachate formation, odour problems, nutrient loss, and long-term land occupation. In contrast, BSF bioconversion can reduce organic-waste volume while recovering nutrients in the form of larval biomass, oil, and frass(20, 23, 111). However, these environmental benefits are context-dependent and should not be generalized without life-cycle assessment. The advantage of BSF farming over landfilling depends on feedstock segregation, rearing efficiency, transport distance, energy use for drying and processing, and the final utilization of larvae and frass (16, 112).

8.3 Resource Use Efficiency

BSF systems are characterized by low land and water requirements relative to conventional protein production systems. Producing 1 kg of BSF protein requires approximately 15–30 m^2 of land, compared to 200–300 m^2 for soybean protein and >1,000 m^2 for beef protein(20). Water consumption is also markedly lower, with BSF protein requiring 4,000–6,000 L kg^{-1}, compared to 15,000 L kg^{-1} for beef and 9,000 L kg^{-1} for soybean(48).

8.4 Nutrient Recycling and Circular Economy Benefits

BSF bioconversion promotes efficient nutrient recycling by redirecting nutrients from waste streams into valuable products, thereby supporting the circular bioeconomy framework (115) (116) BSF systems have been estimated to recover up to 70% of input nitrogen in the combined outputs of larval biomass and frass (23). This closed-loop nutrient flow significantly reduces reliance on synthetic fertilizers and imported feed through an integrated waste-valorization pathway (26, 117).

8.5 Comparison with Other Waste Treatment Technologies

Compared to anaerobic digestion, BSF systems produce higher-value protein outputs while requiring shorter processing times. While composting typically requires 60–90 days to stabilize organic waste, BSF systems achieve comparable stabilization within 10–14 days(13). However, BSF systems are less suitable for very wet substrates and may require pre-treatment for certain waste types. Hybrid systems integrating BSF treatment with anaerobic digestion or composting have therefore been proposed to maximize overall resource recovery (20) Table 3. summarizes the comparative evaluation of organic-waste treatment technologies, highlighting the potential advantages and limitations of BSF bioconversion relative to conventional treatment methods.

Table 3. Comparative evaluation of BSF bioconversion and conventional organic-waste treatment technologies.

Treatment method	Typical processing period	Main outputs	Environmental considerations	Key advantage	Major limitations	Practical suitability
BSF bioconversion	Short active treatment period under controlled rearing conditions	Larval biomass, frass, oil, chitin-containing residues, and residual substrate	May reduce organic-waste burden and recover nutrients; environmental performance depends on feedstock, energy use, drying, transport, and system boundary	Produces multiple recoverable products and supports circular resource use	Requires controlled temperature, moisture, hygiene, approved substrates, product testing, and regulatory compliance	Suitable for segregated organic wastes and agro-industrial by-products where product safety and markets are available

Composting	Several weeks to months	Compost and stabilized organic matter	Supports nutrient recycling but may generate odour, ammonia, and greenhouse-gas emissions if poorly managed	Low-cost, simple, and widely practiced	Requires space, time, aeration, moisture control, and maturity assessment	Suitable for decentralized organic-waste stabilization and soil-amendment production
Anaerobic digestion	Several weeks, depending on feedstock and reactor design	Biogas and digestate	Produces renewable energy but requires digestate management and methane-leakage control	Useful for wet organic wastes and energy recovery	High capital cost, process sensitivity, and need for technical management	Suitable for large-scale wet organic wastes with stable feedstock supply and energy-use infrastructure
Vermicomposting	Several weeks to months	Vermicompost and earthworm biomass	Supports organic-matter stabilization and soil amendment production	Produces nutrient-rich compost under suitable conditions	Sensitive to temperature, moisture, pH, and toxic substrates	Suitable for mild, pre-stabilized organic wastes and small- to medium-scale systems
Incineration	Rapid thermal treatment	Heat, electricity, ash, and flue gas	Reduces waste volume but causes nutrient loss and may produce air pollutants if emission control is inadequate	Rapid treatment of large waste volumes	High capital cost, emission-control requirement, and loss of recoverable organic nutrients	Suitable mainly for non-recyclable or contaminated waste streams rather than nutrient-recovery systems

Table 4, compares BSF bioconversion with conventional organic-waste treatment methods using common criteria such as processing period, outputs, environmental considerations, advantages, limitations, and practical suitability. It highlights that BSF bioconversion is useful for selected segregated organic wastes, but its performance depends on feedstock quality, process control, product safety, and regulatory acceptance.

8.6. Economic Performance Metrics and Operational Resilience

Techno-economic assessments of optimized, industrial-scale BSF facilities indicate robust financial performance, characterized by an internal rate of return (IRR) ranging from 18% to 35%. Corresponding capital payback periods are typically realized within 3 to 5 years, although these metrics remain contingent upon the scale of operation, degree of automation, and the stability of feedstock supply chains (118, 119). Waste disposal fee savings alone can offset 20–40% of operating costs, particularly in urban and agro-industrial settings. This dual-revenue mechanism, which combines service-based waste treatment with product-based biological valorization, may support the long-term economic sustainability of BSF enterprises. A comparative assessment of the major economic factors associated with different organic-waste treatment technologies is presented in Figure 8. Compared to anaerobic digestion and composting, BSF systems offer higher profitability due to diversified revenue streams.

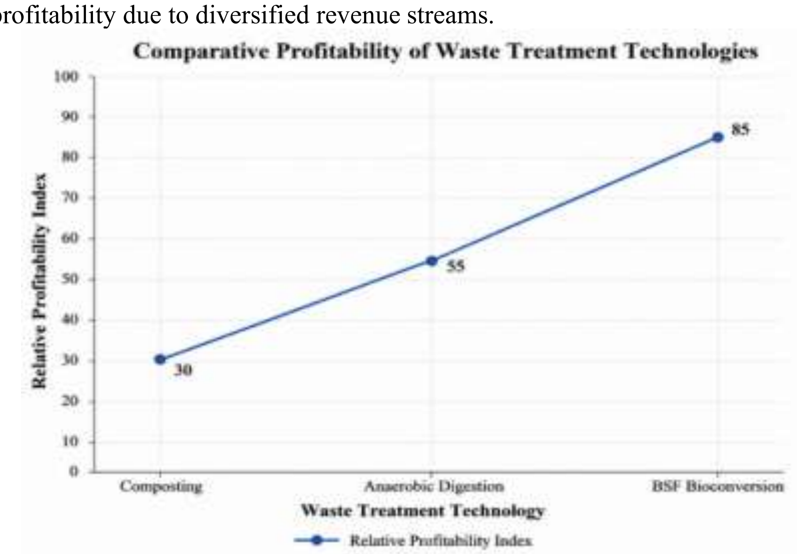

Figure 8. Comparative economic performance of black soldier fly bioconversion, composting, and anaerobic digestion.

9. Challenges, biosafety, and regulatory frameworks

Despite the significant potential of black soldier fly (BSF) bioconversion as a sustainable waste management and resource recovery technology, several technical, biosafety, and regulatory challenges must be addressed to enable large-scale commercialization and global adoption. These challenges are interconnected and influence system efficiency, product safety, and market acceptance(20, 78).

9.1 Technical and Biological Constraints

The performance and stability of BSF bioconversion systems are strongly influenced by substrate quality, environmental conditions, and biological variability. One of the primary constraints is the heterogeneity of organic waste substrates, which can lead to inconsistent larval growth, reduced feed conversion efficiency, and variability in product composition. BSF larvae are highly sensitive to environmental parameters such as temperature, humidity, and aeration. Optimal larval development typically occurs at temperatures between 27–30°C, with deviations resulting in reduced growth rates and prolonged development cycles (13). In temperate regions or low-resource settings, maintaining these conditions can be challenging and may require energy-intensive climate control systems, thereby increasing operational costs.Furthermore, biological risks such as microbial infections, competition with other insect species, and colony collapse can affect system productivity. Although BSFL exhibit resilience and antimicrobial properties, large-scale rearing systems may still experience instability due to poor hygiene practices or suboptimal management (91).

9.2 Biosafety and Feed-Safety Concerns

The safety of BSF-derived products depends mainly on the rearing substrate and post-harvest processing. Heavy metals such as cadmium, lead, and arsenic may accumulate in larval biomass or remain in the residual frass(16, 109). Pesticides, mycotoxins, veterinary medicines, and other chemical contaminants may also persist or be redistributed between larvae and frass (110). Selected antibiotics may be partially degraded during BSF treatment; however, antibiotic-resistant bacteria and antimicrobial-resistance genes may remain or change in abundance during bioconversion (76). Therefore, manure- and waste-derived substrates require monitoring for both antibiotic residues and antimicrobial resistance. BSFL can reduce populations of Salmonella and Escherichia coli, but complete pathogen elimination is not guaranteed (74, 75). Validated heat treatment, hygienic processing, microbiological testing, and prevention of post-processing contamination are consequently required (120). Insect proteins may also cause allergic reactions or cross-react with crustacean and mite allergens. Dust generated during the handling of dried larvae, meal, and exuviae should therefore be controlled through ventilation, protective equipment, worker training, and appropriate labelling.

9.3 Regulatory Landscape

Regulations governing BSF-derived products differ among countries and may specify permitted insect species, acceptable rearing substrates, processing requirements, contaminant limits, traceability, labelling, and approved animal-feed uses. The ability of BSFL to consume a material does not automatically mean that the resulting biomass is legally suitable for animal feed (120). Regulatory frameworks remain incomplete in several countries, particularly regarding permissible substrates, frass maturity, contaminant limits, and product registration. Clear national standards are therefore required to distinguish feed-grade larvae, fertilizer-grade frass, industrial biomass, and products intended only for waste treatment. Pilot-scale and commercial-scale techno-economic studies are also necessary to evaluate operating cost, energy demand, labour requirement, automation, market stability, and regional scalability. stability (17, 121). The critical knowledge gaps and strategic priorities identified are summarized in Table 4.

Table 4. Critical research gaps and future perspectives in black soldier fly bioconversion.

Research domain	Current knowledge gaps	Future research perspectives
Substrate utilization	High variability in waste composition, nutrient balance, moisture, and contamination level affects larval growth and product quality	Develop feedstock standardization, deodourization, substrate classification, and optimized co-feeding strategies
Process standardization	Absence of uniform reporting methods for FCR, WRE, biomass yield, nutrient recovery, and mass balance limits comparison among studies	Establish standard performance indicators, dry-matter-based calculations, and transparent mass-balance reporting
Gut microbiome and biochemical pathways	Limited understanding of how gut microbes and enzymes degrade recalcitrant wastes such as lignocellulosic residues	Conduct microbiome, metagenomic, enzymatic, and substrate-specific degradation studies
Chitin–chitosan recovery	Lack of standard methods for extraction yield, purity, degree of deacetylation, and polymer quality	Develop greener extraction methods and compare yield, molecular weight, functionality, and scalability
Frass agronomy	Limited long-term field validation of frass across soil types, crops, climates, and application rates	Conduct multi-season field trials to assess nutrient release, crop response, soil health, and safety
Biosafety and contaminants	Insufficient data on heavy metals, pesticides, antibiotics, pathogens, allergens, and antimicrobial-resistance risks	Develop safety-monitoring protocols, contaminant limits, heat-treatment validation, and risk-assessment frameworks

Regulatory framework	Regulations remain inconsistent regarding permitted substrates, feed use, frass quality, product registration, and traceability	Establish clear substrate-specific standards, product classification, labelling, and regulatory compliance pathways
Environmental impact	LCA findings vary due to differences in system boundary, energy use, transport, drying, and product substitution assumptions	Conduct location-specific LCA studies with standardized boundaries and comparison with composting, anaerobic digestion, and landfilling
Techno-economic scalability	Limited commercial-scale data on capital cost, labour, automation, energy use, product markets, and profitability	Perform pilot-scale and industrial-scale techno-economic assessments under different regional conditions
Circular bioeconomy integration	BSF systems are often studied separately from other waste-treatment and agricultural value chains	Integrate BSF bioconversion with composting, anaerobic digestion, aquafeed production, frass use, and biorefinery pathways

10. CONCLUSION

Black soldier fly bioconversion offers a promising approach for converting suitable organic wastes into larval biomass, frass, lipids, and chitin-derived products. The process is supported by larval feeding activity, digestive enzymes, and gut-associated microorganisms, while its agricultural value is mainly linked to alternative feed production, nutrient recycling, frass utilization, and the valorization of agro-industrial residues. However, performance varies considerably with substrate composition, moisture, feeding regime, larval density, environmental conditions, processing methods, and analytical procedures. Large-scale adoption is further limited by inconsistent performance reporting, energy and infrastructure requirements, feedstock variability, contaminant and pathogen risks, frass maturity, allergenicity, regulatory restrictions, and uncertain economic viability. Therefore, BSF treatment should be regarded as a feedstock-specific and regulated technology rather than a universal solution for all organic wastes. Future research should prioritize standardized mass-balance and performance metrics, microbiome-assisted degradation of fibrous agricultural residues, long-term field evaluation of frass, contaminant and antimicrobial-resistance monitoring, safer chitin and chitosan extraction, and location-specific life-cycle and techno-economic assessments. Greater integration with composting and anaerobic digestion may further improve resource recovery and system stability. With effective process control, traceability, biosafety governance, and regulatory clarity, BSF bioconversion can contribute meaningfully to circular agriculture and sustainable organic-waste management.

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