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Black soldier fly larvae frass as an organic fertilizer: a review of field application, crop yield, soil health and market potential

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KEYWORDS

Black soldier fly larvae, circular economy, crop yield, frass, soil health, sustainable agriculture

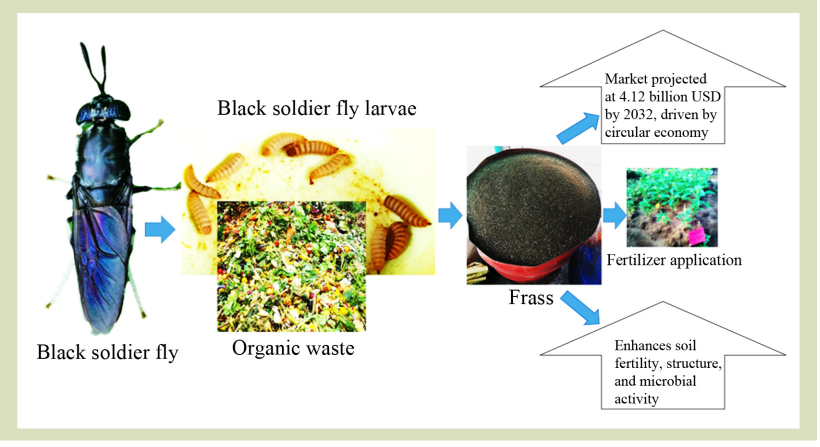
HIGHLIGHTS

- Black soldier fly larvae (BSFL) frass boosts maize/vegetable yields, matching mineral fertilizers at equivalent N rates.
- Enhances soil fertility, structure and microbial activity for long-term health gains.
- Dual nutrient release reduces leaching, and chitin aids pest suppression and resilience.
- BSFL Market projected at 4.12 billion USD by 2032, driven by circular economy and organic fertilizer demand.
- Variability from feedstocks requires standardization for optimal agronomic use.

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GRAPHICAL ABSTRACT



ABSTRACT

With escalating global food demands and environmental concerns from mineral fertilizers, black soldier fly larvae (BSFL, *Hermetia illucens*) frass is a sustainable organic fertilizer from organic waste. This review synthesizes field applications, agronomic impacts, soil health benefits, comparative efficacy and market prospects. Applied via soil incorporation or topdressing at 60–250 kg·ha^{-1} N, frass significantly increases crop yields in maize, vegetables (broccoli, lettuce, potato and tomato) and forages, often equaling or surpassing urea or compost. Yield gains from balanced macro- and micronutrients, high organic matter and biostimulant effects, including upregulated defense genes against herbivores and drought resilience via improved photosynthesis. Frass profoundly enhances soil health: chemically, by boosting nutrients and cation exchange capacity; physically, through aggregation and water retention; biologically, via microbial stimulation and enzyme activity. Compared to mineral fertilizers, it offers slow-release N

(shorter immobilization, 3–10 times higher mineralization), without leaching risks, and chitin-derived pathogen suppression. Market analyses forecast the overall black soldier fly (BSF) sector to reach 4.12 billion USD by 2032 (32.4% compound annual growth rate), with the biofertilizer (frass) segment as a major contributor driven by circular economy and organic demand. Challenges include feedstock variability, regulatory and standardization gaps. Future research on long-term effects, integrated management and life-cycle assessments will accelerate adoption of BSFL frass as a component of circular, resilient agriculture.

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1 Introduction

The escalating global population, projected to surpass 9 billion by 2050, exerts unprecedented pressure on agricultural systems to meet the burgeoning demand for food, feed and fiber[1]. Traditional agricultural practices, heavily reliant on mineral fertilizers, have significantly increased crop yields over the past century. However, this intensification has come at a considerable environmental cost. The production of mineral fertilizers, particularly nitrogen-based ones via the Haber-Bosch process, is energy-intensive, contributing significantly to greenhouse gas emissions[2,3]. Also, their overuse and inefficient application can lead to nutrient runoff into water bodies, causing eutrophication, loss of biodiversity and contamination of drinking water sources[4]. Soil degradation, characterized by nutrient depletion, loss of organic matter, increased salinity and reduced microbial activity, is another detrimental consequence of long-termexcessive use of fertilizers infarming[5–7]. These challenges underscore the urgent need for sustainable agricultural intensification strategies that enhance productivity while minimizing environmental impact and improving resource use efficiency[8].

Organic fertilizers and soil amendments derived from recycled organic waste streams represent a promising avenue towards achieving more sustainable agricultural systems[9]. Utilizing organic wastes not only diverts them from landfills, where they contribute to methane emissions, but also returns valuable nutrients and organic matter to the soil, fostering a circular economy approach[10]. Various organic amendments, such as, biosolids, compost, manures and vermicomposting, have been traditionally used to improve soil fertility and crop performance. However, the consistency, nutrient availability, and potential presence of contaminants (such as heavy metals and pathogens) in these materials can vary, necessitating careful management[11–13].

In recent years, insect farming, particularly using the black soldier fly, *Hermetia illucens*, has emerged as an innovative and efficient technology for converting diverse organic waste streams into valuable biomass[14,15]. BSFL have a the ability to consume large quantities of organic matter, including food waste, animal manure and agricultural byproducts, rapidly converting it into high-quality larval biomass, which is rich in protein and lipids, primarily used for animal feed[2,16–18]. A significant byproduct of this bioconversion process is the larval excreta mixed with undigested organic residues and larval chitin skin, commonly referred to here as frass for simplicity, that has been used as fertilizer, therefore Kullan et al.[16] proposed the term *frasstilizer* for BSFL frass.

BSFL frass is increasingly recognized not just as a waste product but as a valuable organic fertilizer and soil amendment. It contains essential plant macronutrients (N, P and K) and micronutrients, chitin, significant amounts of organic matter and beneficial microorganisms derived from the larval gut and the substrate[2,5,19,20]. The nutrient composition of frass, while variable depending on the substrate fed to the larvae, often compares favorably with other organic fertilizers such as compost or manure[2,12,21]. Beyond nutrient supply, BSFL frass has been reported to improve soil physical properties, enhance soil microbial activity, potentially suppress certain soil borne plant pathogens and nematodes, and stimulate plant growth through mechanisms that may include hormonal effects or improved nutrient availability[5,11,22–25]. Total N content in BSFL frass commonly ranges from 2% to 4% dry matter, with optimized/commercial products often 3.6% to

3.9%[2], though specific substrates yield lower values (e.g., 2.34% in examples shown in Table 1), whereas and phosphorus from 1.3% to 1.6%, exceeding that in many composts, although this varies with feedstock[26]. Studies have also highlight interactions with soil biology, including potential inhibition of arbuscular mycorrhizal fungi (AMF) due to high N and contents[27]. Compared to common organic fertilizers, such as compost or manure, BSFL frass offers distinct advantages: (1) faster nutrient mineralization (3–10 times higher rates and shorter immobilization periods), (2) chitin content (typically 0.045% to 0.39% dry weight, varying by substrate and storage duration-with negative correlation to age due to degradation) that induces plant systemic resistance and suppresses soil borne pathogens/nematodes, (3) more effective hygienization of waste substrates during larval bioconversion, reducing pathogen loads, and (4) stronger alignment with circular economy principles through rapid waste valorization. These features highlight the core value and novelty of BSFL frass in sustainable agriculture.

This review aims to provide a comprehensive overview of the application of BSFL frass as an organic fertilizer, focusing specifically on its practical use in agricultural settings (Fig. 1), and challenges and opportunities. Key unresolved issues include feedstock-driven variability in nutrient/chitin/heavy metal profiles, potential long-term soil accumulation of contaminants, limited data on crop quality impacts beyond yield, incomplete regulatory frameworks for frass products and need for standardized production protocols. This review addresses these by synthesizing field evidence, comparative analyses, and market insights to guide future research and adoption.

Table 1 Comparative nutrient properties of BSFL frass and other fertilizers (% dry matter basis)

Fertilizer type	Total N	Total P	Total K	Organic matter	C:N ratio	Source
BSFL frass	2.34	0.7	1.33	57	14.1	[5]
SAFI (commercial organic)	1.83	0.39	1.16	27	8.7	[5]
Urea (mineral)	46	0	0	0	~0.2	Standard composition
Typical compost	1–3	0.2–1	0.5–2	20–50	10–25	General agricultural knowledge
Typical chicken manure	2–5	1–3	1–3	50–70	5–15	General agricultural knowledge
Vermicompost	1.5–2.5	0.5–1.5	1–2	40–60	12–20	[12]

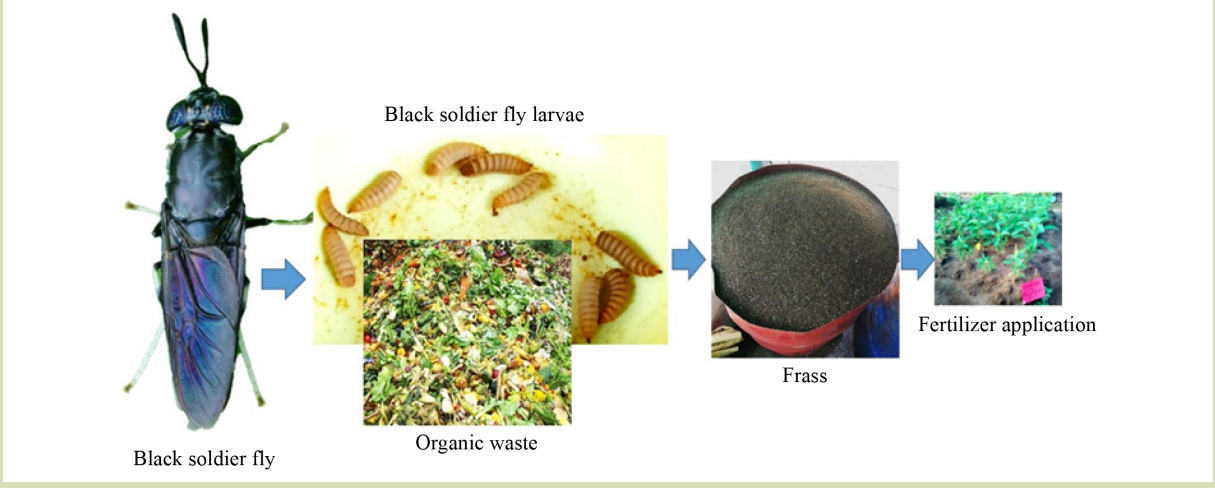


Fig. 1 Black soldier fly frass production from organic waste and field application.

2 Field application of black soldier fly larvae frass

Developing practical application methods for BSFL frass as an organic fertilizer in agricultural fields is an important aspect determining its feasibility and effectiveness. Research has extensively explored its application methods, optimal rates, nutrient dynamics and practical considerations compared to mineral fertilizers or common organic amendments, such as compost or manure. These studies provide insights into optimizing nutrient delivery, maximizing crop response and ensuring sustainable integration into farming systems.

Application methods. BSFL frass is typically available as a dry, granular or powdery material, making it easy to handle and apply using standard fertilizer spreading equipment, similar to compost or pelleted fertilizers[2]. Common application methods include direct incorporation into the soil before planting or top dressing around established plants. For example, Beesigamukama et al.[5] demonstrated that incorporating BSFL frass into the soil prior to sowing maize significantly enhanced growth. The organic matter content of frass contributes to improved soil structure and water retention over time, complementing its immediate nutrient release benefits[28]. Recent studies have also evaluated frass as a partial peat replacement in substrates for Brassicaceae crops, such as kale and mustard, showing improved nutrient uptake and yield[29,30].

Optimal application rates. Determining the application rate for BSFL frass is necessary and depends on factors, such as its nutrient content (influenced by larval diet[2]), crop nutrient requirements, soil fertility status and environmental conditions. Studies often calculate application rates based on N or P equivalents compared to mineral fertilizers. For example, Beesigamukama et al.[5] applied frass at rates supplying 60 kg·ha^{-1} N, comparing these to equivalent urea treatments and a control, establishing dose-response relationships that maximize yield without nutrient imbalances. In an on-farm experiment with *Amaranthus hybridus*, 20 days after transplanting and fertilized with BSFL frass gave better growth than control plot when applied at a rate of 75 kg·ha^{-1} N (Fig. 2)[31]. In forage systems, application rates of 3.4–6.8 t·ha^{-1}of yellow mealworm frass have been shown to enhance soil nutrients and Bermuda grass yield[24]. Recent work on tomatoes indicates biomass increases plateauing at 150–250 kg·ha^{-1} N, with root dry weight stabilizing at ~3 g per plant from 100–200 kg·ha^{-1} N, though higher rates may cause ammonium toxicity symptoms such as leaf curling[27]. Mitigation ofthis includes: (1) pre-application stabilization/composting to convert NH_4^+ to stable forms, (2) limiting rates to 150–200 kg·ha^{-1} N for sensitive crops such as tomato, (3) selecting low-N substrates or blending frass, and (4) soil incorporation with monitoring of EC/pH to prevent burn.

Nutrient release dynamics. BSFL frass serves as both a source of readily available nutrients and a slow-release fertilizer.



Fig. 2 On-farm experiment of *Amaranthushybridus*, 20 days after transplanting and fertilized with black soldier fly larvae frass, applied at a rate of 75 kg·ha^{-1} N. (a) the control plot (no larvae frass); and (b) the plot fertilized with BSFL frass reared on a mixture of soya bean and maize hull. Reproduced from Hall et al.[31], with permission from Centre for Agriculture and Bioscience International (CABI).

Mineralized nutrients, such as NH_4^+-N, provide immediate plant nutrition, while the organic fraction undergoes gradual mineralization, releasing nutrients over time[2,6,11,32]. This dual-release pattern reduces the need for repeated fertilizer applications compared to highly soluble mineral fertilizers[33]. However, nutrient release dynamics are influenced by soil type, temperature, moisture and microbial activity, necessitating site-specific management[34]. *In situ* studies indicate shorter net immobilization periods (30–60 days) and higher mineralization (3–10 times) and nitrification (2–4 times) rates in frass-amended soils compared to commercial organic amendments[6]. Chemical analyses of commercial BSFL frass products reveal high NH_4^+-N (98% of mineral N, up to 2720 mg·kg^{-1}), total N (3.6%–3.9%) and P (13.1–15.6 g·kg^{-1}), with micronutrients such as Fe (665–1240 mg·kg^{-1}) and Zn (102–206 mg·kg^{-1}) varying by product[27].

Variability and standardization. The nutrient profile of BSFL frass varies significantly with the substrate used for larval rearing[2]. Frass from nutrient-rich substrates, such as food waste or specific diets (e.g., Gainesville diet), often has higher NPK than frass from manure or plant residues. This variability requires thorough characterization before application to ensure accurate nutrient management. Standardizing production processes and substrate composition could yield a more consistent fertilizer product[35]. Reviews of frass from food waste substrates emphasize post-processing to ensure maturity and suitability, noting that C/N ratios are often agronomically suitable but moisture levels may need adjustment[36]. Recent reviews underscore that feedstock influences frass quality, with secondary composting potentially reducing salinity and improving efficiency as a fertilizer[26].

Safety and practical considerations. While BSFL frass is generally safe, adherence to good agricultural practices is essential. The BSFL bioconversion process reduces pathogen loads compared to raw manure, but additional processing (e.g., composting or thermal treatment) may be required for crops consumed raw, particularly when using certain substrates[2,37]. Studies confirm suitability of frass for hygienizing organic waste, with reduced coliforms post-application[19]. Repeated applications should be monitored for potential effects on soil pH and salinity, which are typically moderate but could be significant in arid or semi-arid regions[2,38].Seed germination decreases with higher frass extract concentrations, with use of some products giving no germination at rates $\geqslant$ 50% due to phytotoxicity whereas others give 20% germination even at a rate of 100% with ammonium toxicity being the key factor[27].

Heavy metals in frass can come from the rearing substrate (feed and water). During BSFL digestion, substrate mass reduction (via consumption and respiration) can concentrate non-bioaccumulated elements in frass. However, studies show BSFL often bioaccumulate or partition many metals into larvae (reducing frass levels), with final concentrations typically below regulatory limits for feed/fertilizer when clean substrates are used. Long-term repeated application warrants soil monitoring to prevent gradual accumulation, though risks appear lower than with raw manure due to hygienization and lower baseline inputs.

BSFL frass is a versatile organic fertilizer applied through standard methods such as soil incorporation or top dressing. Optimal application rates depend on frass composition, crop needs and soil conditions, with research demonstrating positive responses across various rates. Its dual nutrient release profile offers both immediate and sustained benefits, but variability in composition necessitates careful characterization. Continued research into optimizing application strategies, understanding long-term effects and standardizing frass production will enhance its role as a sustainable fertilizer in diverse agricultural systems.

3 Effect of BSFL frass application on crop yield

A primary measure of the efficacy of any fertilizer is its impact on crop yield and overall plant productivity. Numerous studies have investigated the effects of BSFL frass application on the yield of various crops, often demonstrating significant positive outcomes compared to unfertilized controls and, in many cases, comparable or superior results relative to mineral or other organic fertilizers. The observed yield enhancements are typically attributed to the supply of essential nutrients, the improvement of soil properties, and potentially the presence of plant growth-promoting substances within the frass[2].

Maize yield enhancement. Maize (*Zea mays*), a globally important staple crop with high nutrient demands, has been a frequent subject in studies of BSFL frass application as a fertilizer (Table 2). Beesigamukama et al.[5] conducted field trials in Uganda and reported substantial increases in maize grain yield following BSFL frass application. When applied at rates equivalent to 60 kg·ha^{-1} N, frass resulted in grain yields significantly higher than the unfertilized control. Notably, the

Table 2 Comparative maize grain yield results (BSFL frass versus other fertilizers)[5]

Fertilizer treatment	Application rate	Grain yield in short rain (t·ha^{-1})	Grain yield in long rain (t·ha^{-1})	Comparison note
Control (Unfertilized)	–	~2.8	~3.5	Baseline for comparison
BSFL frass	7.5 t·ha^{-1}	5.4	7.2	Highest yield in t·ha^{-1} trials; 7%–14% higher than SAFI at same rate
SAFI (commercial organic)	7.5 t·ha^{-1}	~5.0	~6.3	Lower yield than BSFL frass at same rate
BSFL frass	Eqv. 100 kg·ha^{-1} N	5.7	6.2	Highest yield in N-eqv. trials; 6%–27% higher than SAFI, 7%–21% higher than urea
SAFI (commercial organic)	Eqv. 100 kg·ha^{-1} N	~5.4	~4.9	Lower yield than BSFL frass and urea at same N rate
Urea (mineral)	Eqv. 100 kg·ha^{-1} N	~5.3	~5.1	Lower yield than BSFL frass at same N rate
BSFL frass	2.5 t·ha^{-1}	–	–	Considered effective rate; required double rate for SAFI for similar yield
BSFL frass	Eqv. 30 kg·ha^{-1} N	–	–	Considered effective rate; required double rate for SAFI for similar yield

Note: Short rain, October to December; long rain, March to May.

yield achieved with frass was statistically comparable to that obtained using the recommended rate of urea, a common mineral N fertilizer, indicating that frass can effectively substitute for mineral N sources in maize production under those specific conditions[5]. The study also observed improvements in other yield components, such as plant height and biomass accumulation, correlating with frass application. Recent work has further shown that insect frass upregulates maize defense genes, enhancing resistance to invasive herbivores such as *Spodoptera frugiperda*, which indirectly supports yield by reducing pest damage[23].

Vegetable crop performance, Similar positive effects have been documented for various vegetable crops (Table 3). Research indicates beneficial effects on crops including cucumber, lettuce, potato and tomato[2,22,41]. The application of frass has been linked to increased marketable yield, larger fruit size, and enhanced vegetative growth. Studies comparing frass with standard compost or vermicompost often find frass performing equally well or better, potentially due to a more readily available nutrient pool or specific growth-promoting compounds. The relatively balanced nutrient profile of frass, including essential micronutrients, likely contributes to improved plant health and productivity across different vegetable species[2]. Additional studies show frass enhances lettuce resilience and photosynthetic efficiency under drought, increasing nutrients such as K and Fe[39,42]. For Brassicaceae, frass as a peat replacement or liquid fertilizer improves yield and nutrient uptake in broccoli, kale mustard[29], where different frass products (solid, liquid and chitin-fortified) enhance growth, yield and nutritional value[40]. Potato yields are also increased, with nematode suppression contributing to

Table 3 BSFL frass application rate and yield impact of various crops

Crop/system	Application rate	Yield impact	Key observation	Reference
Maize	60 kg·ha^{-1} N	Comparable to urea, higher than control	Improved plant height, biomass; pest resistance	[5,23]
Cucumber, lettuce and tomato	Variable	Increased marketable yield, fruit size	Outperforms compost; drought resilience	[2,39]
Brassicaceae (broccoli, kale and mustard)	Peat replacement, liquid fertilizer	Improved yield, nutrient uptake	Enhanced nutritional value	[29,40]
Potato	Variable	Increased yield	Nematode suppression	[22]
Bermuda grass	3.4–6.8 t·ha^{-1}	Enhanced yield, soil health	Outperforms vermicompost	[12,24]

performance[22].Recent greenhouse bioassays with tomatoes (*Solanum lycopersicum*) demonstrate significant biomass increases, with shoot dry weight peaking at 5.5g (wild-type) and 4.5g (mycorrhizal-defective mutant) at 150–200 kg·ha^{-1} N and shoot P concentrations plateauing at ~1.2% from 150–250 kg·ha^{-1} N, though with potential dilution effects in mutants[27]. Reviews confirm the value of BSFL frass for tomatoes, enhancing growth and nutrient uptake, but also note ammonium toxicity at higher rates and the need for optimization[26].

Factors influencing yield response. The magnitude of the yield response to BSFL frass application is influenced by several factors. The application rate is paramount; dose-response studies generally show increasing yield with higher frass rates up to an optimal level, beyond which diminishing returns or negative effects (e.g., due to salinity or nutrient imbalance) might occur[5]. Frass nutrient content is variable and depends on the larval diet. Frass derived from protein-rich substrates may elicit a stronger yield response, particularly in N-limited soils, compared to frass from lower-quality inputs[2]. Comparative studies show BSFL frass outperforms vermicompost in crop yield and soil organic carbon (SOC) enhancement[12].

Soil type interactions. Interactions between frass application and soil type are important. In nutrient-poor or degraded soils, the addition of organic matter and nutrients via frass can lead to more dramatic yield improvements compared to fertile soils[43]. The ability of frass to improve soil structure, water retention and microbial activity[11] can indirectly benefit yield by creating a more favorable environment for root growth and nutrient uptake, especially under stressful conditions such as drought[39,44]. In forage, frass improves Bermuda grass yield and quality by enhancing soil health[24].

Crop quality impacts. Beyond yield quantity, emerging evidence indicates BSFL frass positively influences crop quality. For example, in broccoli, frass application enhanced nutritional value (e.g., higher vitamin/mineral content) and overall marketable traits[40]. In vegetables, such as lettuce and tomato, improved nutrient uptake (K and Fe) and photosynthetic efficiency under stress contribute to better nutritional value and resilience[39]. Mechanisms likely include balanced macro- and micronutrient supply, chitin-derived biostimulant effects inducing defense pathways, and organic matter improving nutrient bioavailability. However, data on quality parameters (e.g., protein/vitamin content, shelf life and sensory traits) remain limited compared to yield studies, representing a priority for future targeted research.

The application of BSFL frass has consistently demonstrated its potential to significantly enhance crop yields across a range of species, including staple grains, such as maize, and various vegetables. Yields obtained with frass are often comparable to those achieved with mineral fertilizers when applied at equivalent nutrient rates, positioning it as a viable organic alternative. The effectiveness is linked to its nutrient supply (both immediate and slow-release), organic matter content, and potential biostimulant properties. Optimizing application rates based on frass characterization, crop requirements, and soil conditions is key to maximizing yield benefits and promoting its adoption in sustainable agricultural practices.

4 Effect of BSFL frass application on soil health

Soil health, defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, is fundamental to sustainable agriculture and environmental quality[7]. Intensive conventional farming practices, often involving monoculture and heavy reliance on mineral fertilizer inputs, can lead to soil degradation, characterized by loss of organic matter, nutrient imbalances, reduced biodiversity and impaired physical structure. Organic amendments are important for mitigating these issues and enhancing soil health. BSFL frass, as a nutrient-rich organic byproduct, is increasingly recognized for its potential to positively influence various aspects of soil health, encompassing its chemical, physical and biological properties.

Chemical properties. One of the most direct impacts of BSFL frass application is the enrichment of soil chemical fertility. Frass supplies essential plant macronutrients (N, P and K) and micronutrients (Ca, Mg, S, Fe, Mn, Zn, Cu and B)[2]. The nutrient content, while variable based on larval feedstock, often provides a balanced source of plant nutrition. Gurung et al.[11] highlighted that frass application can significantly increase soil total N, available phosphorus and exchangeable potassium levels compared to unamended soils. In forage systems, frass increases soil C, N, P, K and Mg, and this direct nutrient addition supports plant growth and can reduce the reliance on mineral fertilizers[24]. Also, frass contributes significantly to soil organic matter (SOM). The high organic matter content

reported in frass (e.g., average 86.2% dry matter[2]) is important for improving soil structure, water retention, and nutrient cycling[45]. As this organic matter decomposes, it gradually releases nutrients (slow-release effect), providing a sustained supply throughout the crop cycle and enhancing the cation exchange capacity of soil, which improves its ability to retain essential positively charged nutrients including K^+, Ca^{2+}, and Mg^{2+}[46]. Studies have also examined the effect on soil pH and electrical conductivity (EC). While frass itself can have a near-neutral to slightly alkaline pH (average 7.46[2]), its impact on soil pH can vary depending on the initial soil pH and the buffering capacity of the soil[47]. Generally, moderate applications are unlikely to cause drastic pH shifts, and the organic matter can contribute to buffering capacity. EC might increase slightly due to the soluble salts in frass, requiring monitoring, especially in sensitive environments or with high application rates[48]. In comparative studies, BSFL frass enhances SOC and nutrient dynamics more effectively than vermicompost[12].

Physical properties. The addition of organic matter through BSFL frass application is key to improving soil physical properties. Organic matter acts as a binding agent, promoting the formation and stabilization of soil aggregates[49]. Improved aggregation leads to better soil structure, characterized by increased porosity, enhanced water infiltration and better aeration[5]. These improvements create a more favorable environment for root growth and proliferation, allowing plants to explore a larger soil volume for water and nutrients[50] Enhanced water infiltration reduces surface runoff and erosion, while increased water holding capacity makes the soil more resilient to drought periods[51]. Studies, such as Beesigamukama et al.[5], indicate that long-term application of organic amendments, including frass, can contribute to rebuilding soil structure in degraded lands. In forage systems, frass increases soil C, N, P, K and Mg, improving overall health scores[24].

Biological properties. BSFL frass is not only a source of nutrients and organic matter; it is also biologically active, containing a diverse community of microorganisms derived from the larval gut and the substrate bioconversion process[2,11]. When added to soil, frass can stimulate soil microbial biomass and activity. The organic carbon and nutrients serve as a food source for indigenous soil microbes, leading to increased populations and enhanced activity of enzymes involved in nutrient cycling (e.g., phosphatases and dehydrogenases)[52]. Gurung et al.[11] specifically investigated the impact of BSFL frass on soil microbial communities and enzyme activities, finding positive effects that indicate enhanced biological functioning. This heightened microbial activity accelerates the decomposition of organic matter and the mineralization of nutrients, making them more available to plants[53]. Also, some research s that BSFL frass may possess properties that suppress certain soil borne plant pathogens. This could be due to the introduction of beneficial antagonistic microbes, the production of specific inhibitory compounds (e.g., chitin derived from insect exoskeletons shed during molting and present in frass), or the induction of systemic resistance in plants[5,22,23,54]. While mechanisms require further elucidation, the potential for disease suppression adds another layer to the soil health benefits of frass. Frass also hygienizes organic waste, reducing pathogens while maintaining suitability as an amendment[19].

The application of BSFL frass has a range of potential benefits for soil health. It enhances chemical fertility by supplying a balanced range of macro- and micronutrients and increasing soil organic matter. It improves physical properties including aggregation, water retention and aeration. Importantly, it stimulates soil biological activity, boosting microbial biomass, enzyme functions and potentially contributing to disease suppression. These combined effects create a healthier, more resilient and productive soil environment, underpinning the potential of BSFL frass as a valuable component of sustainable soil management strategies.

5 Comparison of BSFL frass with other fertilizers

The potential adoption of BSFL frass as a mainstream organic fertilizer hinges significantly on its performance relative to established fertilizer application practices. These include the widespread use of mineral fertilizers, which offer high nutrient concentrations and predictable availability, and common organic amendments, such as composts and manures, valued for their soil-building properties. A comparative analysis reveals that BSFL frass possesses a unique combination of characteristics, positioning it as a competitive and potentially superior alternative in certain contexts, although variability and standardization remain key considerations.

Comparison with mineral fertilizers. Mineral fertilizers (e.g.,

ammonium nitrate, potassium chloride, superphosphate and urea) are characterized by high concentrations of specific nutrients (N, P or K) in readily available forms. This allows for precise nutrient application tailored to crop needs, often resulting in rapid plant growth and high yields, as demonstrated over decades of use in intensive agriculture. However, their production is energy-intensive, they contribute little to soil organic matter, and their overuse can lead to significant environmental problems, such as nutrient leaching, greenhouse gas emissions (N_2O), and soil acidification[2,5,55]. BSFL frass, in contrast, commonly has lower concentrations of NPK compared to mineral fertilizers. For example, average total N in frass can range from 2% to 5% dry matter[2] whereas urea contains 46% N. Table 1 provides a comparison of the nutrient properties of BSFL frass (from a specific study) with other common fertilizers.

Consequently, larger volumes of frass are required to supply equivalent amounts of a specific nutrient, which can have logistical and cost implications. However, studies such as Beesigamukama et al.[5] have shown that when applied at equivalent N rates, BSFL frass can produce maize yields comparable to urea. This indicates that the N in frass, although present at lower concentrations, is effectively used by plants. This efficacy might be partly due to the combination of readily available mineral N (e.g., NH_4^+) and organically bound N that is gradually mineralized, providing a more sustained nutrient release profile compared to the rapid release from highly soluble mineral N sources. This slow-release characteristic can potentially improve N use efficiency and reduce losses through leaching or volatilization[56]. Also, unlike mineral fertilizers, BSFL frass contributes substantial amounts of organic matter and a wide range of micronutrients[2]. These contributions are important for improving long-term soil health-enhancing structure, water retention, and microbial activity-benefits not provided by purely chemical inputs[57]. Therefore, while mineral fertilizers excel in providing concentrated, immediate nutrition, BSFL frass offers a more holistic approach, nourishing the plant while simultaneously improving the soil ecosystem.

Comparison with common organic amendments (compost, manures and vermin compost). Common organic amendments, such as composts and manures (cow, pig and poultry), are widely used to improve soil fertility and organic matter content. BSFL frass shares similarities with these materials but also have distinct differences.

Nutrient content and variability. The nutrient content of BSFL frass is often comparable to or higher than that of many composts and some manures, particularly regarding N and P[2]. For example, frass N content (2%–5% dry matter) can exceed that of typical yard waste compost (< 2% N) or aged cow manure (~2% N), although it might be lower than fresh poultry manure (3%–5% N). However, as with frass, the nutrient content of manures and composts is highly variable, depending on the animal source, diet and storage/handling (manures), as well as feedstock and process (compost). Compositional analysis[2] has directly compares frass from various substrates with manures, highlighting this variability but showing frass can be competitive. A potential advantage of industrially produced frass could be greater consistency if the larval feedstock is controlled, compared to the inherent variability of on-farm manure. Direct comparisons with vermicompost show BSFL frass provides superior crop performance, higher SOC and better nutrient dynamics[12].

Nutrient availability. Nutrients in frass, particularly N and P, are often considered more readily available than those in common composts. The bioconversion process by BSFL may partially degrade complex organic molecules, leading to a higher proportion of mineralized or easily mineralizablenutrients[6,11,58]. This can result in a quicker plant response compared to composts where nutrients are released more slowly as decomposition proceeds in the soil[59].

Organic matter quality. While both frass and compost add organic matter, the nature might differ. Frass contains insect-derived compounds such as chitin, which may have unique effects on soil microbial communities and plant defense mechanisms[5,60]. Compost undergoes a thermophilic process that stabilizes organic matter and reduces pathogens, while frass stabilization might depend on post-processing steps[61].

Pathogens and contaminants. Raw manures can pose risks due to pathogen content. Composting effectively reduces pathogens if done correctly. The BSFL digestion process itself can reduce certain pathogens, but the safety of frass can depend on the initial substrate and any post-processing[2,62]. Heavy metal content is primarily determined by the feedstock in all cases; using clean inputs is important for both frass and compost production[63].

Soil biological effects. Both frass and compost stimulate soil microbial activity by providing carbon and nutrients. However,

the specific microbial communities introduced or stimulated might differ, potentially leading to different effects on nutrient cycling or disease suppression[11].

Beyond nutrient profiles and availability, BSFL frass provides superior environmental benefits over mineral fertilizers (high GHG from Haber-Bosch N production) and some other organic amendments (methane emissions from manure or compost in landfill). Frass production via waste bioconversion reduces landfill methane, sequesters carbon through SOM addition, and lowers overall carbon footprint per unit nutrient delivered, as supported by emerging life-cycle assessments.

In essence, BSFL frass can be seen as a fertilizing compost, providing both significant organic matter and a relatively rich, readily available nutrient supply. Its performance compared to mineral fertilizers highlights its potential as a substitute, particularly when considering long-term soil health. Compared to other organic amendments, it offers potentially higher or more available nutrient content and unique biological properties, though variability remains a challenge that needs addressing through standardized production and characterization.

6 Market potential and prospects for BSFL frass fertilizer

The transition towards sustainable agriculture, driven by environmental concerns associated with conventional practices and growing consumer demand for organic products, creates significant market opportunities for innovative biofertilizers such as BSFL frass. The dual function of BSFL technology in waste valorization and production of valuable outputs (feed protein and frass fertilizer) aligns perfectly with circular economy principles, further enhancing its market appeal. BSF market analyses indicate a rapidly growing interest and investment in insect-based products, with the frass fertilizer segment poised for substantial expansion.

BSFL frass market size and growth projections. Recent market research reports highlight the burgeoning nature of the insect fertilizers market, with BSFL frass being a key component. Meticulous Research[64]projected the overall insect fertilizers market to reach 319.7 million USD by 2029, expanding at a robust compound annual growth rate (CAGR) of 24.3% from 2022 to 2029[64]. While TOI[65], reported that global market for frass was worth 96 million USD in 2023, with the growth of frass production to be much greater[65]. While frass-specific estimates vary (e.g., narrower insect frass fertilizer projections 97 million to 1.2billion USD in recent years with 6% to 8% CAGR), the broader BSF market growth underscores frass potential[17]. Focusing specifically on the BSF market (overall products including protein meal, oil and frass), Polaris Market Research[17] reported a valuation of 330 million USD in 2023, with a projection to reach 4.12 billionUSD by 2032(overall BSF market), having an even higher CAGR of 32.4% for the overall BSF market during the 2024–2032 forecast period[17]. While these figures encompass all BSF products, both reports emphasize the significant contribution and growth potential of the biofertilizer (frass) segment. Polaris Market Research[17] specifically noted that the biofertilizers segment held a substantial revenue share in 2022, driven by its soil-enhancing capabilities and the rising demand for organic farming inputs[17].

Several factors are key drivers for the growth of the BSFL frass fertilizer market.

Waste management imperatives. Increasing global organic waste generation from municipal, agricultural and industrial sources presents a major disposal challenge. BSFL bioconversion offers an effective and sustainable solution, transforming problematic waste streams into valuable fertilizer, thus addressing waste management needs while creating a marketable product[17,64,66].

Demand for organic and sustainable agriculture. The burgeoning organic food industry and heightened consumer awareness regarding the environmental impact of mineral fertilizers are driving demand for effective organic alternatives. BSFL frass, with its demonstrated benefits for crop yield and soil health, fits well within sustainable and organic farming paradigms[64]. Nutrient cycling and circular economy: BSFL technology exemplifies a circular economy approach by recycling nutrients from waste back into the food system via fertilizer (and animal feed). This aligns strongly with sustainability goals and policy initiatives promoting resource efficiency[17,67].

Performance and soil health benefits. As documented in previous sections, the proven efficacy of frass in enhancing crop yields (comparable to mineral fertilizers in some cases) and improving soil health (organic matter addition and

microbial stimulation) makes it an attractive option for farmers seeking productive and sustainable solutions[5,11].

Cost-effectiveness potential. While production costs are still evolving, the potential for BSFL farming to utilize low-cost waste feedstocks indicates that frass could become a cost-competitive fertilizer option, particularly compared to the rising costs and price volatility of mineral fertilizers[17].

7 Challenges and obstacles

Despite the strong potential, the widespread adoption of BSFL frass faces certain challenges.

Regulatory frameworks. The regulatory landscape for insect-derived fertilizers is still developing and varies significantly across regions. Non-standardized regulations regarding production, safety standards (pathogens and contaminants based on feedstock), labeling and permitted uses can create uncertainty and barriers to market entry and trade[64].

Variability and standardization. As previously discussed, the nutrient content and quality of frass can vary considerably depending on the larval diet. Lack of standardization makes it difficult for farmers to predict performance and manage nutrient application accurately. Establishing quality standards and consistent production protocols is important for building market confidence. Low nutrient density in frass (2% to 4% N versus 46% in urea) increases transportation volumes/costs and complicates large-scale mechanized spreading compared to mineral fertilizers, favoring localized production and use in high-value/organic systems.

Awareness and acceptance. While awareness is growing, many farmers and consumers may still be unfamiliar with BSFL frass or harbor negative perceptions related to its origin from waste or insects. Educational initiatives and demonstration trials are needed to showcase its benefits and safety[17,64]. Scale of production: Currently, large-scale production of BSFL frass is still increasing compared to established fertilizer industries. Scaling up production facilities to meet potential demand while maintaining cost-effectiveness and quality control is a key challenge for the industry.

Targeted policy optimizations could include: (1) developing harmonized standards for frass quality testing (nutrient/heavy metal limits aligned with existing organic fertilizer regulations, e.g., EU or USDA), (2) incentives/subsidies for clean substrate use in BSFL production, (3) certification schemes for frass-based products to build farmer trust, and (4) integration into national circular economy policies promoting insect-based waste valorization, drawing from mature frameworks for compost/manure.

8 Prospects and future research

The outlook for BSFL-frass fertilizer appears to be highly promising. Ongoing research continues to refine understanding of its optimal use, long-term effects and potential for specialized applications (e.g., in horticulture, hydroponics and soil remediation purposes). Technological advancements in BSFL rearing and frass processing are likely to improve efficiency and product consistency. Key players identified in BSF market reports, such as Ÿnsect, Protix, InnovaFeed, EnviroFlight and Nutrition Technologies, are actively investing and expanding, indicating strong industry confidence[64]. The Asia-Pacific region is highlighted as a particularly fast-growing market, driven by agricultural needs and supportive policies[64,68]. As regulatory frameworks mature and awareness increases, BSFL frass is well-positioned to capture a significant share of the organic fertilizer market, contributing substantially to more sustainable and circular agricultural systems globally[69]. While current research provides a strong foundation, several areas warrant further investigation. Long-term studies are needed to fully understand the cumulative effects of repeated frass application on soil health dynamics, nutrient cycling and potential buildup of salts or other elements. Research into optimizing application rates and methods for specific crop-soil systems, potentially integrating frass with other nutrient sources (integrated nutrient management), could enhance efficiency. Elucidating the mechanisms behind observed plant growth promotion and disease suppression effects (e.g., through chitin, microbial communities and phytohormones) will provide deeper insights[70]. Recent findings indicate high P levels may reduce reliance on mineral P fertilizers but inhibit AMF, while chitin could stimulate AMF sporulation[26,27]. Also, developing cost-effective methods for standardizing frass quality and potentially tailoring its composition through controlled larval feeding regimes would significantly boost market acceptance[71]. Lifecycle assessments comparing the overall environmental footprint of frass production and use versus conventional fertilizers will also be valuable[72].

9 Conclusions

The comprehensive review of existing literature underscores the significant potential of BSFL frass as a valuable organic fertilizer and soil amendment within the framework of sustainable agriculture. Derived from the efficient bioconversion of organic waste, frass offers a multifaceted solution that addresses critical challenges related to waste management, soil degradation and the overreliance on mineral fertilizers. Field application studies consistently demonstrate that BSFL frass, whether incorporated into the soil or used as a top dressing, can significantly enhance crop yields across a diverse range of species, including staple grains such as maize and various vegetables, such as tomatoes, where biomass plateaus at 150–250 kg·ha^{-1} N. In many instances, yields achieved with frass are comparable to those obtained with mineral fertilizers when applied at equivalent nutrient rates, positioning it as a viable organic alternative. Beyond mere yield enhancement, the application of BSFL frass contributes profoundly to soil health. It enriches the soil chemically by supplying essential macro- and micronutrients and substantial organic matter, which improves the soil's cation exchange capacity and long-term fertility. Physically, it enhances soil structure, water retention, and aeration. Biologically, it stimulates microbial biomass and activity, potentially suppresses certain soilborne pathogens and nematodes, and may induce plant defense mechanisms, partly attributed to its chitin content. However, high N and P levels can potentially eliminate AMF colonization at rates $\geqslant$100 kg·ha^{-1} N, highlighting a trade-off in biological soil health. When compared to other fertilizers, BSFL frass presents a unique profile. It offers a more holistic, soil-building approach than mineral fertilizers, which primarily provide concentrated, readily available nutrients but lack organic matter and can have negative environmental impacts. Compared to common organic amendments, such as compost and manure, frass often exhibits a higher or more readily available nutrient content, though its variability, linked to larval feedstock, necessitates careful characterization and standardization. The market potential for BSFL-frassfertilizeris substantial, driven by the growing demand for organic products, the imperative for sustainable waste management, and the principles of the circular economy. While challenges such as regulatory hurdles, product variability and the need for greater awareness persist, the strong growth projections for the insect fertilizer market highlight its promising future. In summary, BSFL frass represents a promising, sustainable, and effective tool for modern agriculture. It supports productive farming systems while simultaneously improving soil health and contributing to a circular economy by valorizing organic waste. Further research focused on optimizing application strategies, understanding long-term effects, and standardizing production will be important for its widespread adoption and integration into mainstream agricultural practices.

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Compliance with ethics guidelines

Anand Raj Kumar Kullan, Elke Gabriel Neumann, Arumuganainar Suresh, and Hong Lim Choi declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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