Pertanika J. Trop. Agric. Sci. 49 (3): 1247- 1268 (2026)

TROPICAL AGRICULTURAL SCIENCE

Journal homepage: http://www.pertanika.upm.edu.my/

*Review Article*

# Systematic Scoping Literature Review on Black Soldier Fly Larvae Frass Application Methods and Rate

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## ABSTRACT

The growing demand for sustainable agriculture and effective organic waste management has increased interest in the use of black soldier fly larvae (BSFL) frass. It has a high content of nitrogen, phosphorus, potassium, organic carbon, and beneficial microbial communities. However, the frass application methods and rate are not clearly stated. Thus, this review objective is to determine the frass application methods and rate. This review synthesises data from 16 studies conducted across various soil types, climates, and cropping systems to evaluate the agronomic, ecological, and microbiological effects of BSFL frass application. Direct soil incorporation is most common and effective for the soil and plant benefit. Frass improves plant and soil health. Low-to-moderate frass application rates (2-25 t/ha) enhance plant growth, nutrient uptake, and yield, particularly in nutrient-poor soils. However, higher application rates can cause phytotoxic effects, salinity stress, and microbial imbalance. This emphasises the importance of identifying crop- and context-specific optimum doses. Despite promising outcomes, significant research gaps remain, such as long-term field validation, interactions with diverse soil microbiomes, the fate of potentially harmful elements like heavy metals, and standardised processing and quality control of frass.

*Keywords:* Black soldier fly larvae frass, BSFL frass; circular bioeconomy systems; insect-based frass; soil amendment

ARTICLE INFO

*Article history:*
Received: 03 June 2025
Accepted: 04 May 2026
Published: 26 June 2026

DOI: https://doi.org/10.47836/pjtas.49.3.13

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## INTRODUCTION

The global agricultural sector is gradually challenged by the need to produce more food while reducing dependence on synthetic fertilisers. Synthetic fertiliser is not only

e-ISSN: 2231-8542

energy-intensive to produce but also contributes to environmental degradation, including soil acidification, nutrient runoff, and greenhouse gas emissions (Sabina et al., 2025). Simultaneously, the accumulation of organic waste from urban, agricultural, and agro-industrial sources presents a major sustainability concern. Insect-based bioconversion, particularly using the Black Soldier Fly (BSFL; Hermetia illucens) has emerged recently as a promising circular bioeconomy solution that addresses both waste management and sustainable fertiliser production.

Black soldier fly larvae (BSFL) can efficiently convert a wide range of organic residues into high-value insect biomass (for use in animal feed), insect oil and a nutrient-rich frass (Abd El-Hack et al., 2020; Gurung et al., 2024; Huang et al., 2024; Oteri et al., 2021; Putri et al., 2023; Quigley et al., 2025; Watson et al., 2021). BSFL frass is comprised of undigested substrate, insect excreta, shed exoskeletons, and associated microorganisms (Abd Manan et al., 2024). With this, it has gained attention as a potential biofertiliser due to its essential plant nutrient content (N, P, K), organic matter, and beneficial microbes (Abd Manan et al., 2024). Early studies suggest that frass application can enhance plant growth, improve soil fertility, and stimulate microbial activity (Beesigamukama, Mochoge, Korir, Fiaboe, et al., 2020; Beesigamukama, Mochoge, Korir, Musyoka, et al., 2020). Frass is a viable alternative to synthetic fertilisers and compost in both organic and conventional farming systems.

Despite growing interest, the agronomic performance of BSFL frass varies widely depending on factors such as larval diet, frass processing method, application rate, soil type, and crop species (Lomonaco et al., 2024; Malheiro et al., 2024; Watson et al., 2021). Research to date has been fragmented. It is often limited to short-term or greenhouse trials and lacks standardised methodologies. There is a need to synthesise existing findings to understand the conditions under which BSFL frass is most effective, identify potential limitations or risks (e.g., salinity, heavy metal accumulation), and determine optimal application strategies.

This paper compiles and analyses recent experimental studies on BSFL frass use in agriculture, comparing its effects on plant productivity, soil chemical and biological properties, and environmental outcomes. By identifying patterns, benefits, and trade-offs across diverse systems, the review aims to find out the black soldier fly larvae frass application to soil and clarify the current knowledge landscape. Also, this paper highlights research gaps and proposes directions for the sustainable and scalable use of insect frass in soil fertility management.

This review addresses the following three research questions:

- What methods of BSFL frass application to soil and plants are used in current experimental studies?
- What application rates of BSFL frass have been reported for soil and plant systems?

- What effects do different application rates and methods have on plant productivity and soil properties?

## THEORETICAL FRAMEWORK

### Soil Fertility and Nutrient Use Efficiency (NUE)

Soil fertility is the soil's capacity to supply essential nutrients to plants in adequate amounts and proper balance (Havlin, 2020). BSFL frass contains macronutrients (N, P, K) and micronutrients (e.g., Fe, Zn, Mn) critical for plant development. The Nutrient Use Efficiency (NUE) theory supports that the form, timing, and availability of nutrients determine plant uptake efficiency and crop productivity (Sarkar & Baishya, 2017).

BSFL frass provides readily available nitrogen (as $NH_4^+$ and $NO_3^-$), organic carbon that improves soil structure and microbial activity, phosphorus, and potassium in slow-release forms (Beesigamukama, Mochoge, Korir, Fiaboe, et al., 2020; Chavez et al., 2023; Malheiro et al., 2024). When BSFL frass is applied at optimal rates, it can match or exceed the performance of synthetic fertilisers in enhancing plant nutrient uptake and yield, while minimising nutrient losses to the environment.

### Organic Matter Dynamics and Soil Health

BSFL frass is rich in organic matter, which contributes to the formation of soil aggregates, water-holding capacity, and cation exchange capacity (Bashir et al., 2021; Menino et al., 2021). The soil health model recognises that organic inputs can restore degraded soils by supporting biological activity, reducing erosion, and improving nutrient cycling (Culas et al., 2025). The incorporation of frass into soil stimulates microbial processes that decompose organic residues, release nutrients, and enhance microbial biomass and enzymatic activity (Salomon et al., 2025). Repeated frass application can improve long-term soil health by building soil organic carbon and supporting a more resilient microbial ecosystem (Ashworth et al., 2025; Salomon et al., 2025).

### Microbial Ecology and Soil-Plant-Microbe Interactions

BSFL frass introduces microbial populations and stimulates existing communities in the rhizosphere (Gurung et al., 2024). According to microbial ecology theory, changes in microbial diversity and function can influence nutrient availability, plant growth promotion, and pathogen suppression (Ambrosini et al., 2016; Chen et al., 2024; Meena et al., 2017). For instance, beneficial genera (e.g., Bacillus, Actinobacteria) may be enhanced, and functional gene expression (e.g., nirK, nosZ) may be stimulated, affecting nitrogen cycling (Lomonaco et al., 2024; Rummel et al., 2021). The biological activity within frass mediates positive feedback loops between soil microbes and plants, leading to improved nutrient uptake and plant stress tolerance (Poveda, 2021).

### Waste Valorisation and Circular Economy Theory

The use of BSFL frass is aligned with circular economy principles, which emphasise the transformation of waste into valuable resources to reduce environmental impact and close nutrient loops (Abd Manan et al., 2024). Organic wastes (e.g., food scraps, manure, brewery waste) are converted by BSFL into insect biomass and frass (Carroll et al., 2023; Gurung et al., 2024; Wu et al., 2023). Frass returns nutrients to the soil, reducing reliance on mined or industrially produced fertilisers (Amorim et al., 2024). BSFL frass serves as a functional bridge between waste management and sustainable agriculture, enabling resource efficiency and reducing external inputs in farming systems (Abd Manan et al., 2024).

### Dose-Response and Environmental Thresholds

The dose-response model in environmental science explains that while low-to-moderate rates of input may be beneficial, higher concentrations can lead to toxicity, salinity stress, or ecological disruption (Chele et al., 2021). Over-frass application may increase soil electrical conductivity (EC), alter pH, or introduce heavy metals (e.g., Zn, Cu) from substrate residues (Watson et al., 2021).

Microbial diversity may decline at high application rates, potentially accompanied by shifts toward fast-growing (r-strategists) microbial taxa (Maron et al., 2018). There exists an optimum frass application threshold beyond which benefits plateau or reverse, emphasising the need for careful dose calibration.

## METHODOLOGY

### Literature Survey Methodology

Based on the PRISMA guideline, a scoping literature review, thematic analysis, and tabular analysis were adopted (Moher et al., 2009). The review intended to address the three research questions: What application rates of black soldier fly larvae (BSFL) frass have been reported for soil and plant systems? What methods of BSFL frass application to soil and plants are used in current experimental studies? What effects do different application rates and methods have on plant productivity and soil properties? Research Registry and OSF (Open Science Framework) were searched to ensure a similar scoping review study protocol was not registered. There was no previous research found that addressed the present area of interest.

## Search Strategy

The electronic scoping search will be conducted in mid-May 2025. The databases searched included PubMed, ScienceDirect, Scopus, and Emerald Insight. The current review covers four major research subjects, including livestock, aquaculture, and agronomy studies. Besides, two main variables using Medical Subject Headings (MeSH) and keywords are applied in this study, as shown in Table 1 and Supplementary Materials (the detailed keywords search, especially for ScienceDirect, since the maximum number of keywords searched is 8). The search string is applied only to the title, abstract, and keywords.

Table 1
*Keywords used in the database search*

| Black Soldier Fly | | Black Soldier Fly Larvae Frass | | Application Rate |
|---|---|---|---|---|
| | | "black soldier fly larvae frass" | | "application rate" |
| | | OR | | OR |
| "Hermetia illucens" | | "bsfl frass" | | "soil to frass ratio" |
| OR | | OR | | OR |
| "black soldier fly" | AND | "black soldier fly frass" | AND | "frass to soil ratio" |
| OR | | OR | | OR |
| bsf | | "bsf frass" | | "frass percentage" |
| | | OR | | OR |
| | | "insect frass" | | "frass-soil mix*" |

*Note*. The asterisk (*) indicates truncation in the search strategy, allowing retrieval of records containing different endings of the root word. For example, mix* includes mix, mixed, mixing, and mixture

## Inclusion Criteria

The inclusion and exclusion criteria of the scoping review included (a) language of the studies: studies published in the English language are included. Studies published in a language other than English are excluded. (b) Type of studies: Formal research studies, including journal articles, were only reviewed to ensure the quality of the included studies. Review articles, including narrative and systematic reviews, were excluded to ensure that only primary, empirical studies reporting original research findings were synthesised. This approach was taken to avoid duplication of data and maintain a consistent methodological basis for comparison across included studies. (c) The focus of the studies: based on the study's objective, the included studies must focus on the black soldier fly frass application rate. Studies focusing on anything other than black soldier fly feeding and growth are excluded. (d) Quality assessment: the selected studies should pass the quality assessment of the BEME framework as described in the quality assessment section to ensure the quality of the scoping review. The excluded studies are either irrelevant or failed the quality assessment of the BEME. Figure 1 shows the search flowchart.

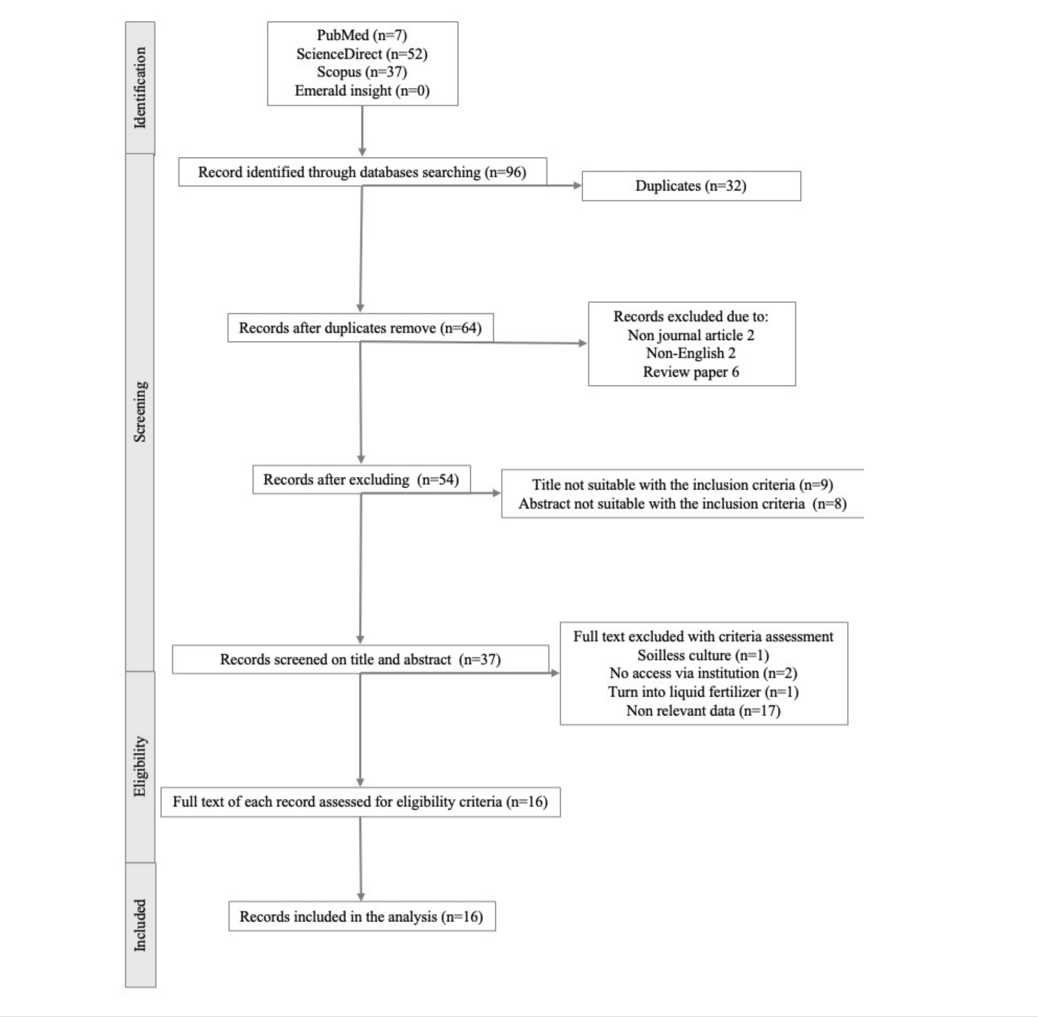

*Figure 1.* PRISMA flow diagram

## Study Quality Assessment

The quality assessment tool is critical in detecting the quality of the not rigorously conducted. The BEME quality framework is used to evaluate the quality of the selected studies (Buckley et al., 2009). The BEME quality framework included 11 indicators for quantitative studies. It is provided with a consistent approach to assessing the selected studies. Each indicator in the BEME is evaluated as 1 = met or 0 = unmet. Each study should complete a minimum of seven indicators to be deemed high quality. Studies scoring below three are rated as weak, studies scoring four to seven are rated as moderate, and those scoring seven and above are rated as strong and included (Buckley et al., 2009). The process of quality assessment is shown in Table 2 and Supplementary Materials.

Table 2
*Average BEME quality assessment results from two authors, who followed the guidelines (Buckley et al., 2009)*

| Quality Indicator | Details | Beesigamukama et al. (2020) | Beesigamukama et al. (2020) | Borkent and Hodge (2021) | Carroll et al (2023) | Chavez et al. (2023) | Chiam et al. (2021) | Gurung et al. (2024) | Huang et al. (2024) | Malheiro et al. (2024) | Mostafaie et al. (2025) | Putri et al. (2023) | Rodgers et al. (2024) | Rummel et al. (2021) | Sawinska et al. (2024) | Watson et al. (2021) | Wu et al. (2023) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Research question | Is the research question (s) or hypothesis clearly stated? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Study subjects | Is the subject group appropriate for the study being carried out (number, characteristics, selection, and homogeneity)? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 'Data' collection methods | Are the methods used (qualitative or quantitative) reliable and valid for the research question and context? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Completeness of 'data' | Have subjects dropped out? Is the attrition rate less than 50%? For questionnaire-based studies, is the response rate acceptable (60% or above)? | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 2 (*continued*)

| **Quality Indicator** | **Details** | **Beesigamukama et al. (2020)** | **Beesigamukama et al. (2020)** | **Borkent and Hodge (2021)** | **Carroll et al (2023)** | **Chavez et al. (2023)** | **Chiam et al. (2021)** | **Gurung et al. (2024)** | **Huang et al. (2024)** | **Malheiro et al. (2024)** | **Mostafaie et al. (2025)** | **Putri et al. (2023)** | **Rodgers et al. (2024)** | **Rummel et al. (2021)** | **Sawinska et al. (2024)** | **Watson et al. (2021)** | **Wu et al. (2023)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Control for confounding | Have multiple factors/ variables been removed or accounted for where possible? | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Analysis of results | Are the statistical or other methods of results analysis used appropriately? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Conclusions | Is it clear that the data justify the conclusions drawn? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Reproducibility | Could the study be repeated by other researchers? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Prospective | Does the study look forward in time (prospective) rather than backward (retrospective)? | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Ethical issues | Were all relevant ethical issues addressed? | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Triangulation | Were the results supported by data from more than one source? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
|  | Total | 9 | 9 | 9 | 8 | 8 | 8 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |

### Search Outcome

A total of 96 studies were identified from the four electronic databases, as shown in the Supplementary Materials. After extracting duplicated studies and including studies published in English, a total of 54 studies remained, of which 37 were excluded based on the title and abstract screening. A text of 16 studies was screened, from which 4 studies were excluded as they included no relevant data (n=17).

## RESULTS AND DISCUSSIONS

### Description of the Selected Studies

The selected studies were 16 based on the selected keywords. The utilisation of Black Soldier Fly (BSF) frass as a soil amendment and organic fertiliser across diverse geographical, agronomic, and soil conditions was studied in the past 5 years from 2020 (Table 3). Since no time frame is specified, the scientific studies of frass application on soil available are limited. The studies ranged from controlled pot and greenhouse experiments to field trials. The selected study involved a wide array of crops, including cereals (maize, oats, barley), vegetables (lettuce, tomato, broccoli, chilli), and herbs (basil, parsley). To produce frass, the selected studies used brewery waste, food and kitchen residues, oil palm waste, and mixed manures as larvae fed and reflected a wide spectrum of nutrient profiles and potential environmental implications.

Frass application rates ranged broadly, from nutrient-equivalent applications (e.g., 0.03-0.1 t/ha on an N basis) to volume- or weight-based doses as high as 187 t/ha in some pot trials. The impacts of frass application were measured on plant growth parameters (biomass, nutrient uptake, yield), soil nutrient dynamics (e.g., N mineralisation, EC, pH, organic matter), and soil biological responses (e.g., microbial diversity, functional gene expression, presence of beneficial or pathogenic taxa).

### Effect of Frass Application Methods

BSFL frass has been applied using diverse experimental approaches (Table 4). They ranged from direct soil incorporation and N-equivalent dosing to combined mineral fertiliser strategies and soil incubation studies. Direct basal application remains the most agronomically relevant method, while nutrient-equivalent and combined approaches facilitate comparison with conventional fertilisers. Pot and incubation studies provide mechanistic insights but require careful extrapolation to field conditions.

Different BSFL frass application methods exert distinct effects on plant productivity and soil properties (Table 5). Direct soil incorporation at moderate rates most consistently enhanced crop yield and soil fertility, particularly in degraded soils.

Table 3
*Selected studies related to Black Soldier Fly Larvae frass and the optimum application rate*

| **Author (Year)** | **Location** | **Soil Type** | **Larval Diet** | **Crop(s)** | **Application Rate (t/ha)** | **Plant Effects** | **Soil Effects** | **Soil Organism Effects** | **Optimum Rate (t/ha)** |
|---|---|---|---|---|---|---|---|---|---|
| (Beesigamukama, Mochoge, Korir, Musyoka, et al., 2020) | Nairobi, Kenya | Acric Ferralsols (acidic, low OM) | Brewery waste | Maize | 0.03, 0.06, 0.1 (N basis) | Yield 20-27% higher than SAFI; best at 100 kg N/ha | Fast N release, late-season deficiency | Not reported | 0.03 t N $ha^{-1}$ recommended; 0.1 t N $ha^{-1}$ highest yield |
| (Beesigamukama, Mochoge, Korir, Fiaboe, et al., 2020) | Nairobi, Kenya | Acric Ferralsols (acidic, shallow, low OM) | Brewery waste | Maize | 0, 1.4, 2.9, 4.8 | Best yield at 7.5 t/ha; better NUE than SAFI/urea | Not reported | Not reported | 2.5 t/ha + 30 kg N/ha |
| (Borkent & Hodge, 2021) | Dublin, Ireland | High-nutrient compost & low-nutrient mix | Brewery waste | Basil, lettuce, etc. | 0.1-0.8 | Growth improved in 8/10 crops; basil and lettuce were best | Stronger effect in high-nutrient soils | Not reported | 0.4-0.7 |
| (Carroll et al., 2023) | Dublin, Ireland | Low-/high-nutrient potting mix | Brewery waste | Oats, barley, spelt | 0.2-1.6 | Growth improved; best at 6-8 g/pot; >8g reduced survival | Effect greater in low-nutrient soil | Not reported | 0.6-0.8 |
| (Chavez et al., 2023) | Colorado, USA | Peat mix | Distillery grains | Tomato | 22.5, 45, 90 | No significant yield gain; 40% reduced Brix and biomass | High NPK, pH 9.5, micronutrient toxicity risk | Not reported | 22.5-45 |

Table 3 (*continued*)

| Author (Year) | Location | Soil Type | Larval Diet | Crop(s) | Application Rate (t/ha) | Plant Effects | Soil Effects | Soil Organism Effects | Optimum Rate (t/ha) |
|---|---|---|---|---|---|---|---|---|---|
| (Chiam et al., 2021) | Singapore | Sandy loam | Chicken feed → okara | Lettuce | 10, 20, 30 | 10% frass + fert = max biomass; 30% reduced growth | High N, C; reduced soil pH | 30% reduced diversity; 10% preserved microbial health | 10 |
| (Gurung et al., 2024) | Western Australia | Coarse sand | Mixed animal wastes | Chilli | 1.7-10 | Best growth at 0.6%; reduced at higher rates | $NH_4^+/NO_3^-$ increased; high rates raised pH/EC | 0.6% boosted beneficial microbes; 1.2% reduced benefits | 5.0 |
| (Huang et al., 2024) | Guangdong, China | Haplic Acrisol | Kitchen waste | Not specified | 0-70 | Not specified | EC, $NH_4^+$, $NO_3^-$, DOC ↑; nutrients declined over 28 days | Bacterial diversity ↑ at ≥2.5%; fungi ↓ at high rates | 35 |
| (Malheiro et al., 2024) | Portugal | Sandy loam (Lufa 2.2) | Vegetable by-products + cereals | Onion, Turnip, Tomato | 1.6-99.8 | Low-mid rates helped; high rates inhibited germination | OM, K, P, pH ↑; salinity is low overall | Enchytraeids ↑, Collembolans are unaffected | Turnip: 12.5-25; Onion: 12.5; Tomato ≤12.5 |
| (Mostafaie et al., 2025) | Portugal | Loamy sand (Lufa 2.2) | Olive pomace + Gainesville feed | Ryegrass, Broccoli | 5.85-187.2 | 2.4-4.8% improved root traits; 9.6% phytotoxic | Not reported | Not reported | 46.8-93.6 |

Table 3 (*continued*)

| Author (Year) | Location | Soil Type | Larval Diet | Crop(s) | Application Rate (t/ha) | Plant Effects | Soil Effects | Soil Organism Effects | Optimum Rate (t/ha) |
|---|---|---|---|---|---|---|---|---|---|
| (Putri et al., 2023) | Indonesia | Not specified | Oil palm waste | Red amaranth | 120-600 | Best at 10% (120 t/ha); 30-50% reduced growth | 10% improved fertility; 30-50% caused metal toxicity | Not reported | 120 |
| (Rodgers et al., 2024) | Dublin, Ireland | Low-nutrient mix | Brewery waste | Ryegrass, Timothy | 0.125-0.75 (N basis) | Timothy & PRG grew better; Timothy is best at a high rate | Not reported | Not reported | >0.75 (needs further testing) |
| (Rummel et al., 2021) | Germany | Haplic Luvisol | Carb/protein-based frass | Not specified | 0.127-0.422 (N basis) | Not specified | Protein-frass: N mineralisation; Carb-frass: N immobilisation | GHG emissions ↑; microbial biomass ↑ | ~14 (low emission), ~43 (high performance) |
| (Sawinska et al., 2024) | Poland | Commercial OM-rich soil | BSF frass | Lettuce | 1.6-2.0 | Max yield 30.4 g/pot at 12.5 g frass | Not reported | Not reported | 2 |
| (Watson et al., 2021) | Germany | Sandy loam | Wheat bran | Not applicable | 48.75-97.5 | Not reported | High OM; nutrient-rich; heavy metal toxicity mitigated | Stimulated fungi & microbes | 97.5 |
| (Wu et al., 2023) | Not specified | Not specified | Food waste | Maize | 21-126 | Biomass ↑ at 1-4%; ↓ at 6% (salinity) | Not reported | Not reported | 42 |

*Note.* *SAFI: commercial organic fertiliser made from composted chicken manure, biochar, and rock phosphate in Mwea town, Kirinyaga County, Kenya

Table 4
*Methods of BSFL frass application to soil and plants in experimental studies*

| Application Method | Description | Unit/ Expression of Rate | Typical Experimental setup | Representative Studies | Main Purpose/Rationale |
|---|---|---|---|---|---|
| Direct soil incorporation (basal application) | Frass is mixed uniformly into the soil or growth medium before planting | t/ha (field); % w/w or g/pot (pots) | Field plots, pots, greenhouse trials | (Beesigamukama, Mochoge, Korir, Fiaboe, et al., 2020; Beesigamukama, Mochoge, Korir, Musyoka, et al., 2020; Chiam et al., 2021; Gurung et al., 2024; Malheiro et al., 2024; Wu et al., 2023) | Mimics farmer practice; evaluates effects on crop growth, soil fertility, salinity, and microbial communities |
| Nutrient-equivalent (N-based) application | Frass applied according to its N content, aligned with recommended fertiliser N rates | kg N/ha or frass mass equivalent | Field and pot trials with fertiliser comparisons | (Beesigamukama, Mochoge, Korir, Musyoka, et al., 2020; Rodgers et al., 2024; Rummel et al., 2021) | Enables direct comparison with mineral fertilisers; assesses nutrient use efficiency (NUE) |
| Combined frass + mineral fertiliser | Frass applied at moderate rates with supplemental mineral N or commercial fertiliser | t/ha frass + kg N/ha; % | Field and pot experiments | (Beesigamukama, Mochoge, Korir, Fiaboe, et al., 2020; Chiam et al., 2021) | Integrated nutrient management maximises yield while reducing fertiliser inputs and toxicity risks |
| Percentage or mass-based pot application | Frass added as a proportion of soil mass/volume or as g per pot | % w/w; g/pot (converted to t/ha) | Controlled pot and greenhouse studies | (Borkent & Hodge, 2021; Carroll et al., 2023; Mostafaie et al., 2025; Sawinska et al., 2024) | Allows precise dosing and mechanistic assessment; useful for threshold and toxicity studies |
| Soil incubation (no plants) | Frass mixed into the soil and incubated without crops | % w/w or kg N/ha | Laboratory incubation studies | (Huang et al., 2024; Rummel et al., 2021) | Isolates soil biochemical and microbial responses; assesses N mineralisation and GHG emissions |

Table 5

*Effects of BSFL frass application methods on plant productivity and soil properties*

| Application Method | Effects on Plant Productivity | Effects on Soil Chemical Properties | Key Advantages | Key Limitations/ Risks |
|---|---|---|---|---|
| Direct soil incorporation (basal application) | Consistent increases in biomass and yield at moderate rates (10-45 t/ha); Improved nutrient uptake and NUE; Yield suppression at excessive rates | ↑ Mineral N ($NH_4^+$, $NO_3^-$), P, K, organic C; Improves fertility in acidic, nutrient-poor soils; High rates ↑ EC and risk salinity | Practical and compatible with conventional fertiliser management; supports both plant growth and soil fertility | Over-application causes phytotoxicity, salinity stress, and nutrient imbalance |
| Nutrient-equivalent (N-based) application | Yield comparable to mineral fertilisers (e.g., urea, SAFI) High NUE and early vigour; Possible late-season N limitation | Rapid N mineralisation; May improve in soil organic matter | Allows direct fertiliser comparison; efficient nutrient delivery | Does not fully capture the soil-conditioning benefits of frass |
| Combined frass + mineral fertiliser | Highest and most stable yields; Reduced yield variability compared with frass alone | Balanced nutrient supply; Lower EC and reduced risk of toxicity | Optimises productivity and soil health; supports integrated nutrient management | Requires careful rate optimisation and fertiliser access |
| Percentage / mass-based pot application | Strong growth response at low-moderate percentages (≤5%); Growth inhibition at high percentages (>5-10%) | Rapid nutrient release; High rates sharply increase EC and pH | High experimental control; identifies toxicity thresholds | Field-equivalent rates often unrealistically high; limited extrapolation |
| Soil incubation (no plants) | Not assessed | Clarifies N mineralisation vs. immobilisation; High rates increase $CO_2$ and $N_2O$ emissions | Reveals mechanisms driving soil responses | Cannot directly predict crop yield responses |

Nutrient-equivalent applications often produced yields comparable to mineral fertilisers while also contributing additional soil-conditioning benefits, although nutrient release tends to be slower than synthetic fertiliser. Combined frass-mineral fertiliser strategies often provided a more balanced nutrient supply and supported crop productivity while potentially reducing risks associated with salinity and nutrient imbalance risks when applied at appropriate rates. Pot-based and incubation approaches clarified response thresholds and biogeochemical mechanisms but require cautious extrapolation to field conditions.

## Effect of Frass Application Rate

Based on most of the selected studies, moderate application rates of BSFL frass improved plant growth and nutrient use efficiency (NUE), often bettering or equaling conventional fertilisers like urea or SAFI (semi-arid fertiliser input) (Beesigamukama, Mochoge, Korir, Fiaboe, et al., 2020; Beesigamukama, Mochoge, Korir, Musyoka, et al., 2020). Generally, frass rates ranging from 10 to 45 t/ha were observed as optimal plant responses, such as enhanced root and shoot biomass, chlorophyll content, and nutrient uptake (Gurung et al., 2024; Putri et al., 2023; Wu et al., 2023). Yet, in controlled pot experiments, the optimal concentration was often expressed as a percentage of soil mass or volume (e.g., 2.4-4.8%), and the amount was generally high when converted to the unit of tan/ha (Putri et al., 2023; Wu et al., 2023).

Frass also had evident positive effects on soil quality, mainly by increasing levels of mineral nitrogen ($NH_4^+$, $NO_3^-$), organic carbon, and essential nutrients (P, K, Zn). In acidic and nutrient-poor soils (e.g., Acric Ferralsols in Kenya or Tenosols in Australia), frass application promptly improved fertility and supported early crop development. Yet, excessive frass application (30t/ha (Chiam et al., 2021); 99.8t/ha (Mostafaie et al., 2025); 360-600t/ha (Putri et al., 2023)) led to negative consequences such as germination *suppression*, reduced biomass, accumulation of heavy metals (e.g., Zn, Mn, Cu, B), and raised soil electrical conductivity (EC), which is often due to salinity stress or nutrient imbalances.

Microbial responses were equally critical. In optimal ranges, frass enhanced microbial biomass carbon (MBC) and nitrogen (MBN), supported beneficial bacterial populations (e.g., Kribbella, Nocardioides), and promoted functional genes related to C and N cycling (Gurung et al., 2024; Huang et al., 2024; Rummel et al., 2021). However, high application rates (30t/ha) disrupted microbial communities by reducing diversity and promoting opportunistic taxa like Acinetobacter, which may be linked to reduced plant performance (Chiam et al., 2021; Rummel et al., 2021). In a few studies (Huang et al., 2024; Rummel et al., 2021), frass behaved more like fresh manure than compost, with high $CO_2$ and $N_2O$ emissions, especially from carbohydrate-rich substrates, indicating a trade-off between fertility gains and environmental sustainability (Huang et al., 2024; Rummel et al., 2021).

Overall, BSFL frass shows robust potential as a sustainable, circular biofertiliser and is suitable for integrated nutrient management in low-input or degraded schemes. When the frass is wisely applied, it can improve crop productivity, soil fertility, and microbial function. Yet to avoid phytotoxicity or ecological disruption, application rates always depended on crop type, soil conditions, and frass composition. Across the selected studies, the optimum frass rate generally fell between 10 and 45 t/ha (Table 6). In contrast, particularly in nutrient-demanding crops, low application rates produced only marginal benefits. Excessive frass inputs (≥30 t/ha) resulted in phytotoxic effects, elevated soil electrical conductivity, and microbial community disruption, indicating that over-application may compromise both productivity and environmental sustainability. Yet, some crop-specific limits diverge significantly depending on soil texture, baseline fertility, and frass quality. The evidence supports BSFL frass as a valuable component in sustainable agriculture and organic waste recycling. Yet future studies should further refine dosing guidelines, assess long-term soil health impacts, and explore synergies with other organic amendments.

Table 6
*Effects of BSFL Frass application rates on crops, soil fertility, and soil microorganisms*

| **Application Rate Category** | **Typical Application Range*** | **Effects on Crop Growth and Yield** | **Effects on Soil Fertility** | **Effects on Soil Microorganisms** |
|---|---|---|---|---|
| Low rate | <10 t/ha (field)<br>≤2% soil mass/ volume (pot) | Minor or inconsistent improvements in seedling vigour and early growth; Generally inferior to moderate frass rates and mineral fertilisers (e.g., urea, SAFI); Often insufficient to meet crop N demand | Slight increases in available N, P, and K; Minimal changes in soil organic carbon and CEC; Benefits are more apparent in nutrient-poor or acidic soils | Neutral to slightly positive effects on microbial biomass (MBC, MBN); Limited changes in microbial community composition or functional diversity |
| Moderate rate (optimal) | 10-45 t/ha (field-equivalent) ~2.4-4.8% soil mass/ volume (pot) | Significant increases in shoot and root biomass; Higher chlorophyll content and photosynthetic activity; Improved nutrient uptake and nutrient use efficiency (NUE); Often equal to or better than conventional fertilisers | Increased mineral N ($NH_4^+$, $NO_3^-$) and soil organic carbon; Enhanced availability of P, K, and micronutrients (e.g., Zn); Improved fertility in degraded or low-input soils without excessive EC | Increased microbial biomass carbon and nitrogen; Enrichment of beneficial taxa (e.g., Kribbella, Nocardioides); Enhanced functional genes related to C and N cycling |
| High rate | ≥30 t/ha (field)<br>>5% soil mass/ volume (pot)<br>Extreme cases: 99.8-600 t/ha (converted) | Reduced germination and seedling establishment; Decreased biomass and yield; Phytotoxic effects due to salinity and nutrient imbalance | Elevated soil EC (salinity stress); Accumulation of heavy metals/ micronutrients (Zn, Mn, Cu, B); Nutrient antagonism and impaired soil quality | Reduced microbial diversity and community stability; Dominance of opportunistic taxa (e.g., Acinetobacter)<br>• Increased $CO_2$ and $N_2O$ emissions, resembling fresh manure effects |

*Note.**Application ranges vary depending on soil type, crop species, and frass composition

## Potential Research Gaps

There is a lack of standardisation in frass composition and quality to produce the nutrient frass. For example, large variability in larvae feedstock (e.g., brewery waste, kitchen scraps, animal manure) leads to inconsistent frass nutrient profiles (e.g., N, P, K, micronutrients) and physicochemical properties (pH, EC, C: N ratio). There is no universally accepted quality standard or classification system for BSFL frass (e.g., based on NPK levels, heavy metals, and pathogen load). Research rarely evaluates microbial safety, persistence of antibiotics or pathogens, or potential allelopathic compounds. Future research should focus on defining clear standards for BSFL frass composition, nutrient content labelling, and safety testing protocols.

There is also a limited understanding of long-term soil and environmental effects. Most studies are short-term and conducted under controlled conditions (greenhouse, pot trials), with few long-term or multi-season field experiments. Soil health over time, such as microbial community stability, nutrient leaching, and buildup of salts or heavy metals, is largely unexamined. Greenhouse gas (GHG) emissions from frass-amended soils (e.g., $CO_2$, $N_2O$, $CH_4$) are poorly studied in terms of across different climatic zones and soil types. Longitudinal studies are needed to monitor the cumulative impacts of repeated frass application on soil ecology, crop health, and environmental emissions.

Moreover, there are also no studies on interaction with other inputs such as fertilisers, biochar, and compost. Synergistic or antagonistic effects of BSFL frass when combined with other organic or inorganic fertilisers are underexplored. Limited investigation into how frass performs in integrated nutrient management systems, or as a partial replacement for synthetic fertilisers. Studies should assess optimised frass-blended fertilisation strategies for maximising plant response while reducing input costs and environmental burden.

Furthermore, crop- and soil-specific dosing guidelines are incomplete. While some studies report optimum rates, most findings are context-specific and not scalable or generalisable. Little guidance exists for applying BSFL frass across different soil textures, pH levels, salinity conditions, or crop developmental stages. A decision-support framework is needed to guide farmers in determining safe and effective frass application rates tailored to local agroecological conditions.

Additionally, plant-soil-microbe interactions are underexplored. Microbial shifts in frass application rate, such as both beneficial and detrimental, are observed. Yet, the mechanistic insights into how frass application rate affects plant-microbe symbioses, root microbiome recruitment, and disease suppression or promotion are lacking. Few studies explore frass effects on mycorrhizal fungi, soil enzymes, or microbial functional traits critical for nutrient cycling and soil structure. Metagenomic and metabolomic tools should be studied to unravel how frass influences plant-soil-microbe interactions across different settings.

Plus, economic and agronomic feasibility in real-world farming systems is limited by the application rate of frass. Most studies are not linked to cost-benefit analyses, labour and resource requirements, or logistics of sourcing and applying frass at scale. Farmer adoption, especially in low-income or smallholder settings, is poorly understood. Socioeconomic studies and on-farm participatory research are essential to assess the feasibility, acceptance, and scalability of BSFL frass in different agricultural contexts.

## CONCLUSION

Based on the 16 selected studies, BSFL frass has the potential to become a sustainable fertiliser. Direct soil incorporation is most common and effective, while N-based or combined applications improve nutrient use efficiency; pot and incubation studies clarify mechanisms but are less field-relevant. However, there is no specific application rate. Moderate rates via incorporation or combined fertilisation enhance plant growth and soil fertility; high rates can cause salinity, nutrient imbalance, and reduced productivity. The studied application rate ranges from 10 to 45 t/ha, which is too high to apply in practice. Yet, more future research is needed to move beyond proof-of-concept and address standardisation, scalability, environmental safety, and long-term ecosystem effects. Interdisciplinary efforts involving agronomy, microbiology, soil science, and economics are essential to bridge these gaps and integrate BSFL frass into regenerative agriculture models.

## ACKNOWLEDGEMENT

The authors would like to thank all individuals who provided support throughout this study.

## REFERENCES

Abd El-Hack, M. E., Shafi, M. E., Alghamdi, W. Y., Abdelnour, S. A., Shehata, A. M., Noreldin, A. E., Ashour, E. A., Swelum, A. A., Al-Sagan, A. A., Alkhateeb, M., Taha, A. E., Abdel-Moneim, A.-M. E., Tufarelli, V., & Ragni, M. (2020). Black soldier fly (*Hermetia illucens*) meal as a promising feed ingredient for poultry: A comprehensive review. *Agriculture*, *10*(8), Article 339. https://doi.org/10.3390/agriculture10080339

Abd Manan, F., Yeoh, Y.-K., Chai, T.-T., & Wong, F.-C. (2024). Unlocking the potential of black soldier fly frass as a sustainable organic fertiliser: A review of recent studies. *Journal of Environmental Management*, *367*, Article 121997. https://doi.org/10.1016/j.jenvman.2024.121997

Ambrosini, A., de Souza, R., & Passaglia, L. M. P. (2016). Ecological role of bacterial inoculants and their potential impact on soil microbial diversity. *Plant and Soil*, *400*(1), 193-207. https://doi.org/10.1007/s11104-015-2727-7

Amorim, H. C. S., Ashworth, A. J., Arsi, K., Rojas, M. G., Morales-Ramos, J. A., Donoghue, A., & Robinson, K. (2024). Insect frass composition and potential use as an organic fertiliser in circular economies. *Journal of Economic Entomology*, *117*(4), 1261-1268. https://doi.org/10.1093/jee/toad234

Ashworth, A. J., Amorim, H. C. S., Drescher, G. L., Moore, P. A., Rojas, M. G., Morales-Ramos, J., & Donoghue, A. M. (2025). Insect frass fertiliser as soil amendment for improved forage and soil health in circular systems. *Scientific Reports*, *15*(1), Article 3024. https://doi.org/10.1038/s41598-025-87075-8

Bashir, O., Ali, T., Baba, Z. A., Rather, G. H., Bangroo, S. A., Mukhtar, S. D., Naik, N., Mohiuddin, R., Bharati, V., & Bhat, R. A. (2021). Soil organic matter and its impact on soil properties and nutrient status. In G. H. Dar, R. A. Bhat, M. A. Mehmood, & K. R. Hakeem (Eds.), *Microbiota and biofertilisers, Vol 2: Ecofriendly tools for reclamation of degraded soil environs* (pp. 129-159). Springer International Publishing. https://doi.org/10.1007/978-3-030-61010-4_7

Beesigamukama, D., Mochoge, B., Korir, N. K., Fiaboe, K. K. M., Nakimbugwe, D., Khamis, F. M., Subramanian, S., Dubois, T., Musyoka, M. W., Ekesi, S., Kelemu, S., & Tanga, C. M. (2020). Exploring black soldier fly frass as novel fertiliser for improved growth, yield, and nitrogen use efficiency of maize under field conditions. *Frontiers in Plant Science*, *11*, Article 574592. https://doi.org/10.3389/fpls.2020.574592

Beesigamukama, D., Mochoge, B., Korir, N., Musyoka, M. W., Fiaboe, K. K. M., Nakimbugwe, D., Khamis, F. M., Subramanian, S., Dubois, T., Ekesi, S., & Tanga, C. M. (2020). Nitrogen fertiliser equivalence of black soldier fly frass fertiliser and synchrony of nitrogen mineralisation for maize production. *Agronomy*, *10*(9), Article 1395. https://doi.org/10.3390/agronomy10091395

Borkent, S., & Hodge, S. (2021). Glasshouse evaluation of the black soldier fly waste product HexaFrass™ as an organic fertiliser. *Insects*, *12*(11), Article 977. https://doi.org/10.3390/insects12110977

Buckley, S., Coleman, J., Davison, I., Khan, K. S., Zamora, J., Malick, S., Morley, D., Pollard, D., Ashcroft, T., Popovic, C., & Sayers, J. (2009). The educational effects of portfolios on undergraduate student learning: A Best Evidence Medical Education (BEME) systematic review. BEME Guide No. 11. *Medical Teacher*, *31*(4), 282-298. https://doi.org/10.1080/01421590902889897

Carroll, A., Fitzpatrick, M., & Hodge, S. (2023). The effects of two organic soil amendments, biochar and insect frass fertiliser, on shoot growth of cereal seedlings. *Plants*, *12*(5), Article 1071. https://doi.org/10.3390/plants12051071

Chavez, M. Y., Uchanski, M., & Tomberlin, J. K. (2023). Impacts of black soldier fly, (Diptera: Stratiomyidae) larval frass on tomato production. *Journal of Economic Entomology*, *116*(5), 1490-1495. https://doi.org/10.1093/jee/toad150

Chele, K. H., Tinte, M. M., Piater, L. A., Dubery, I. A., & Tugizimana, F. (2021). Soil salinity, a serious environmental issue and plant responses: A metabolomics perspective. *Metabolites*, *11*(11), Article 724. https://doi.org/10.3390/metabo11110724

Chen, Q., Song, Y., An, Y., Lu, Y., & Zhong, G. (2024). Soil microorganisms: Their role in enhancing crop nutrition and health. *Diversity*, *16*(12), Article 734. https://doi.org/10.3390/d16120734

Chiam, Z., Lee, J. T. E., Tan, J. K. N., Song, S., Arora, S., Tong, Y. W., & Tan, H. T. W. (2021). Evaluating the potential of okara-derived black soldier fly larval frass as a soil amendment. *Journal of Environmental Management*, *286*, Article 112163. https://doi.org/10.1016/j.jenvman.2021.112163

Culas, R. J., Anwar, M. R., & Maraseni, T. N. (2025). A framework for evaluating benefits of organic fertiliser use in agriculture. *Journal of Agriculture and Food Research*, *19*, Article 101576. https://doi.org/10.1016/j.jafr.2024.101576

Gurung, S. K., Mickan, B. S., Middleton, J. A., Singh, P. K., Jenkins, S. N., Rengel, Z., Siddique, K. H. M., & Solaiman, Z. M. (2024). Manure-derived black soldier fly frass enhanced the growth of chilli plants (*Capsicum annuum* L.) and altered rhizosphere bacterial community. *Applied Soil Ecology*, *202*, Article 105605. https://doi.org/10.1016/j.apsoil.2024.105605

Havlin, J. L. (2020). Soil: Fertility and nutrient management. In *Landscape and Land Capacity* (2nd ed.). CRC Press. https://doi.org/10.1201/9780429445552-34

Huang, Z., Xu, S., Zheng, N., Yin, X., Yang, Y., & Yao, H. (2024). Salty bio-converted organic fertiliser modulates soil greenhouse gas emissions. *Journal of Cleaner Production*, *445*, Article 141192. https://doi.org/10.1016/j.jclepro.2024.141192

Lomonaco, G., Franco, A., De Smet, J., Scieuzo, C., Salvia, R., & Falabella, P. (2024). Larval frass of *Hermetia illucens* as organic fertiliser: Composition and beneficial effects on different crops. *Insects*, *15*(4), Article 293. https://doi.org/10.3390/insects15040293

Malheiro, C., Prodana, M., Patinha, C., Morgado, R. G., & Loureiro, S. (2024). Insect frass from upcycling vegetable by-products with cereals: Effects on the soil properties, plant development and soil invertebrate fitness. *Journal of Environmental Management*, *372*, Article 123234. https://doi.org/10.1016/j.jenvman.2024.123234

Maron, P.-A., Sarr, A., Kaisermann, A., Lévêque, J., Mathieu, O., Guigue, J., Karimi, B., Bernard, L., Dequiedt, S., Terrat, S., Chabbi, A., & Ranjard, L. (2018). High microbial diversity promotes soil ecosystem functioning. *Applied and Environmental Microbiology*, *84*(9), Article e02738-17. https://doi.org/10.1128/AEM.02738-17

Meena, M., Swapnil, P., Zehra, A., Aamir, M., Dubey, M. K., Goutam, J., & Upadhyay, R. S. (2017). Beneficial microbes for disease suppression and plant growth promotion. In D. P. Singh, H. B. Singh, & R. Prabha (Eds.), *Plant-microbe interactions in agro-ecological perspectives: Volume 2: Microbial interactions and agro-ecological impacts* (pp. 395-432). Springer. https://doi.org/10.1007/978-981-10-6593-4_16

Menino, R., Felizes, F., Castelo-Branco, M. A., Fareleira, P., Moreira, O., Nunes, R., & Murta, D. (2021). Agricultural value of black soldier fly larvae frass as organic fertiliser on ryegrass. *Heliyon*, *7*(1), Article e05855. https://doi.org/10.1016/j.heliyon.2020.e05855

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *BMJ*, *339*, Article b2535. https://doi.org/10.1136/bmj.b2535

Mostafaie, A., Silva, A. R. R., N. Pinto, J., Prodana, M., Lopes, I. G., Murta, D., Brooks, B. W., Loureiro, S., & Cardoso, D. N. (2025). Towards circularity for agro-waste: Minimal soil hazards of olive pomace bioconverted frass by insect larvae as an organic fertiliser. *Journal of Environmental Management*, *375*, Article 124151. https://doi.org/10.1016/j.jenvman.2025.124151

Oteri, M., Di Rosa, A. R., Lo Presti, V., Giarratana, F., Toscano, G., & Chiofalo, B. (2021). Black soldier fly larvae meal as alternative to fish meal for aquaculture feed. *Sustainability*, *13*(10), Article 5447. https://doi.org/10.3390/su13105447

Poveda, J. (2021). Insect frass in the development of sustainable agriculture. A review. *Agronomy for Sustainable Development*, *41*(1), Article 5. https://doi.org/10.1007/s13593-020-00656-x

Putri, H. H., Lakitan, B., Negara, Z. P., & Muda, S. A. (2023). Growth of red amaranth (*Amaranthus cruentus* L.) cultivated on soil-based substrate amended with a residue of the black soldier fly larvae containing heavy metals. *HAYATI Journal of Biosciences*, *30*(2), 302-312. Scopus. https://doi.org/10.4308/hjb.30.2.302-312

Quigley, J. D., Zontini, A., Schroeder, G. F., Roman-Garcia, Y., Houbiers, L., & Bach, A. (2025). Nutritional value of black soldier fly larvae oil in calf milk replacers. *Journal of Dairy Science*, *108*(3), 2481-2488. https://doi.org/10.3168/jds.2024-25666

Rodgers, E., Nicolson, E., Lauder, S., & Hodge, S. (2024). Response of pasture grasses to organic fertiliser produced from black soldier fly frass. *Plants*, *13*(7), Article 943. https://doi.org/10.3390/plants13070943

Rummel, P. S., Beule, L., Hemkemeyer, M., Schwalb, S. A., & Wichern, F. (2021). Black soldier fly diet impacts soil greenhouse gas emissions from frass applied as fertiliser. *Frontiers in Sustainable Food Systems*, *5*, Article 709993. https://doi.org/10.3389/fsufs.2021.709993

Sabina, R., Paul, J., Sharma, S., & Hussain, N. (2025). Synthetic nitrogen fertiliser pollution: Global concerns and sustainable mitigating approaches. In N. Hussain, C.-Y. Hung, & L. Wang (Eds.), *Agricultural nutrient pollution and climate change: Challenges and opportunities* (pp. 57-101). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-80912-5_3

Salomon, M. J., Cavagnaro, T. R., & Burton, R. A. (2025). Potential of black soldier fly larvae frass (BSFL) as a novel fertiliser: Impacts on tomato growth, nutrient uptake, and mycorrhizal formation. *Plant and Soil, 501*(1-2), 115-129. https://doi.org/10.1007/s11104-024-07187-4

Sarkar, D., & Baishya, L. K. (2017). Nutrient use efficiency. In M. Naeem, A. A. Ansari, & S. S. Gill (Eds.), *Essential plant nutrients: Uptake, use efficiency, and management* (pp. 119-146). Springer International Publishing. https://doi.org/10.1007/978-3-319-58841-4_6

Sawinska, Z., Radzikowska-Kujawska, D., Kowalczewski, P. Ł., Grzanka, M., Sobiech, Ł., Skrzypczak, G., Drożdżyńska, A., Ślachciński, M., & Świtek, S. (2024). *Hermetia illucens* frass fertilisation: A novel approach for enhancing lettuce resilience and photosynthetic efficiency under drought stress conditions. *Applied Sciences*, *14*(6), Article 2386. https://doi.org/10.3390/app14062386

Watson, C., Schlösser, C., Vögerl, J., & Wichern, F. (2021). Excellent excrement? Frass impacts on a soil's microbial community, processes and metal bioavailability. *Applied Soil Ecology*, *168*, Article 104110. https://doi.org/10.1016/j.apsoil.2021.104110

Wu, N., Yu, X., Liang, J., Mao, Z., Ma, Y., Wang, Z., Wang, X., Liu, X., & Xu, X. (2023). A full recycling chain of food waste with straw addition mediated by black soldier fly larvae: Focus on fresh frass quality, secondary composting, and its fertilising effect on maize. *Science of The Total Environment*, *885*, Article 163386. https://doi.org/10.1016/j.scitotenv.2023.163386

## SUPPLEMENTARY MATERIALS

Supplementary Table S1

*Databases searched and records retrieved*

| Database | Search Date | Records Identified |
|---|---|---|
| PubMed | 15 May 2025 | 7 |
| ScienceDirect | 15 May 2025 | 52 |
| Scopus | 15 May 2025 | 37 |
| Emerald Insight | 15 May 2025 | 0 |
| **Total** | | 96 |

Supplementary Table S2

*Detailed search strategies used in each database*

| Database | Search String |
|---|---|
| PubMed | ("Hermetia illucens" OR "black soldier fly" OR BSF) AND ("black soldier fly larvae frass" OR "BSFL frass" OR "black soldier fly frass" OR "BSF frass" OR "insect frass") AND ("application rate" OR "soil to frass ratio" OR "frass to soil ratio" OR "frass percentage" OR "frass-soil mix*") |
| ScienceDirect - Search 1 | (“black soldier fly”) AND ("black soldier fly larvae frass" OR "black soldier fly frass" OR "bsf frass" OR “insect frass”) AND ("application rate" OR "soil to frass ratio" OR "frass to soil ratio" OR "frass percentage") |
| ScienceDirect - Search 2 | ("Hermetia Illucens" OR "black soldier fly" OR bsf) AND ("black soldier fly larvae frass" OR "black soldier fly frass" OR "insect frass") AND ("application rate" OR "frass-soil mixture") |
| Scopus | ("Hermetia Illucens" OR "black soldier fly" OR bsf) AND ("black soldier fly larvae frass" OR "bsfl frass" OR "black soldier fly frass" OR "bsf frass" OR "insect frass") AND ("application rate" OR "frass to soil ratio" OR "frass percentage" OR "frass-soil mix*") |
| Emerald Insight | ("Hermetia Illucens" OR "black soldier fly" OR bsf) AND ( "black soldier fly larvae frass" OR "bsfl frass" OR "black soldier fly frass" OR "bsf frass" OR "insect frass" ) AND ( "application rate" OR "soil to frass ratio" OR "frass to soil ratio" OR "frass percentage" OR "frass-soil mix*") |

*Note.* The asterisk (*) indicates truncation in the search strategy, allowing retrieval of records containing different endings of the root word. For example, mix* includes mix, mixed, mixing, and mixture