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INSECT FRASS: NATURE'S HIDDEN TREASURE FOR SOIL FERTILITY: A REVIEW

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ABSTRACT

The growing demand for sustainable agricultural practices has led to an increased interest in insect farming and its by-products. Insect frass, consisting of insect excreta, exuviae, and residual feed particles, is emerging as a promising biofertilizer due to its rich nutrient profile and microbial communities. Frass has been shown to enhance plant growth, improve soil fertility, and indirectly contribute to pest management, making it a valuable resource in the circular bioeconomy. This review summarizes current knowledge on the composition, benefits, mechanisms of action, challenges, and future perspectives of insect frass valorization, highlighting its potential role as a sustainable alternative to synthetic fertilizers.

Key words: insect frass, biofertilizer, soil health, sustainable agriculture, circular bioeconomy

Introduction

The rapid expansion of the global population and intensification of agriculture have increased the demand for fertilizers to sustain crop productivity. However, the excessive reliance on synthetic fertilizers has resulted in soil degradation, nutrient imbalances, greenhouse gas emissions, and water contamination, raising concerns about long-term agricultural sustainability (Foley *et al.*, 2011; Savci, 2012). This has accelerated the search for alternative, eco-friendly soil amendments that can simultaneously improve soil fertility, promote plant health, and reduce environmental footprints.

In recent years, insect farming has emerged as a promising bio-based industry, primarily driven by the use of insects as feed for livestock, aquaculture, and companion animals (Van Huis, 2020). A major by-product of insect rearing is insect frass, a heterogeneous material composed of insect excreta, undigested feed particles, exuviae, and associated microorganisms (Klammsteiner *et al.*, 2020). Traditionally considered waste, frass is increasingly recognized as a valuable resource due to its rich composition of essential plant nutrients (N, P, K, and micronutrients), bioactive compounds such as chitin, and diverse microbial communities beneficial for soil and plant health (Beesigamukama *et al.*, 2021; Houben *et al.*, 2020). Like humic substances (eg. liquid potassium humate) that stimulate soil biota and improve nutrient cycling (Satyanarayana *et al.*, 2023), insect frass acts as a biofertilizer, enriching soil organic matter and promoting plant health.

Emerging studies demonstrate that frass application can enhance plant growth and yield while stimulating beneficial soil microbial activity (Quilliam *et al.*, 2020). Moreover, the chitin content in frass has been shown to induce systemic resistance in plants, reducing their susceptibility to insect pests and pathogens (Sharp, 2013; Poveda *et al.*, 2019). Thus, insect frass represents a multifunctional biofertilizer that aligns with the principles of the circular bioeconomy, where organic waste streams are valorized into high-value agricultural inputs.

Despite its potential, the use of insect frass as a biofertilizer remains underexplored, with challenges such as variability in nutrient composition, lack of standardization, and limited large-scale field validation

(Lalander *et al.,* 2019). This review aims to synthesize current knowledge on the composition, agronomic potential, and challenges of insect frass, highlighting its role as a sustainable soil amendment and its future prospects in integrated pest and nutrient management systems.

Composition of Insect Frass

The composition of insect frass is highly variable and depends on the insect species, developmental stage, diet, and rearing substrate (Lalander *et al*., 2019; Klammsteiner *et al.,* 2020). Generally, frass consists of a mixture of insect excreta, undigested feed residues, shed cuticles (exuviae), and microbial populations associated with the insect gut and substrate. This complex composition provides a unique profile of nutrients, bioactive compounds, and beneficial microbes that can enhance soil fertility and plant health.

Macronutrients and Micronutrients

Insect frass is a valuable source of essential plant nutrients, particularly nitrogen (N), phosphorus (P), and potassium (K). The nutrient concentrations vary depending on the insect diet. For instance, black soldier fly (*Hermetia illucens*) frass often contains between 2–4% N, 1–2% P, and 1–3% K (Beesigamukama *et al*., 2021; Klammsteiner *et al*., 2020). In addition, frass provides micronutrients such as calcium, magnesium, zinc, and iron, which are crucial for plant physiological processes (Houben *et al*., 2020). Unlike conventional composts, frass often exhibits a more balanced nutrient profile and faster mineralization rate, making nutrients readily available for plant uptake.

Organic Matter and Chitin

A distinctive feature of insect frass is its chitin content, derived from insect exoskeleton residues and gut passage (Sharp, 2013). Chitin is a structural polysaccharide that can serve as a carbon source for chitinolytic microbes, stimulating beneficial soil microbial activity and suppressing plant pathogens (Poveda *et al.,* 2019). Moreover, chitin and its derivatives act as elicitors of plant defence responses, triggering induced systemic resistance (ISR) against insect herbivores and diseases. In addition to chitin, frass contains organic carbon and humic substances that contribute to soil organic matter enrichment.

Microbial Communities

Frass harbours a diverse microbiome, largely originating from the insect gut and rearing substrate. Studies on black soldier fly and mealworm frass have identified bacterial taxa such as *Bacillus*, *Pseudomonas*, *Enterococcus*, and *Lactobacillus*, many of which are known plant growth-promoting rhizobacteria (PGPR) (Yang *et al*., 2021). These microbes can enhance nutrient cycling, produce phytohormones, and suppress soil-borne pathogens. Some fungi, including *Trichoderma* spp., have also been detected in frass, suggesting potential synergy with biocontrol agents (Klammsteiner *et al*., 2020).

Secondary Metabolites and Bioactive Compounds

Beyond nutrients and microbes, insect frass contains bioactive molecules such as peptides, antimicrobial compounds, and residual plant-derived metabolites from the insect diet (Quilliam *et al*., 2020). These compounds may further enhance plant growth or contribute to pest and pathogen suppression.

Overall, the unique combination of nutrients, chitin, microbial inoculants, and bioactive compounds positions insect frass as a multifunctional biofertilizer, capable of improving soil fertility while simultaneously promoting plant health and resilience.

Mechanisms of Action of Insect Frass in Plants and Soil

The agronomic benefits of insect frass are not solely attributed to its nutrient content but also to its ability to enhance soil microbial communities, stimulate plant defense pathways, and suppress pests and pathogens. The mechanisms can be grouped into nutrient-driven effects, biological interactions, and plant-mediated responses.

Nutrient Release and Soil Fertility Enhancement

Insect frass acts as a slow-release organic fertilizer, supplying essential nutrients such as nitrogen, phosphorus, and potassium in forms that are more readily mineralized compared to conventional composts (Houben *et al*., 2020). The balanced nutrient profile of frass improves soil fertility, enhances cation exchange capacity, and promotes better root development and nutrient uptake by plants (Beesigamukama *et al*., 2021). Additionally, the relatively low C:N ratio of frass accelerates decomposition, ensuring timely nutrient availability during critical growth stages.

Stimulation of Beneficial Soil Microbiota

Frass application promotes the growth of beneficial soil microorganisms, including plant growth-promoting rhizobacteria (PGPR) and biocontrol fungi (Yang *et al.*, 2021). Chitin and organic matter present in frass serve as substrates for microbial proliferation, stimulating chitinolytic and cellulolytic communities that enhance nutrient cycling and soil health. These microbes can produce phytohormones such as indole-3-acetic acid

Table 1: Typical nutrient composition of insect frass (varies with insect species and feedstock).

Insect species (larval frass)	N (%)	P_2O_5 (%)	K_2O (%)	Organic matter (%)	Notable features	References
Black soldier fly (*Hermetia illucens*)	2.0–4.0	1.0–2.0	1.5–3.0	40–60	Rich in chitin; beneficial microbes	Klammsteiner *et al.*, 2020; Amorim *et al.*, 2024; Beesigamukama *et al.*, 2020
Mealworm (*Tenebrio molitor*)	2.5–3.5	0.8–1.5	1.0–2.0	50–65	Higher organic matter; good soil conditioner	Houben *et al.*, 2021
House cricket (*Acheta domesticus*)	2.0–2.8	0.7–1.2	1.2–2.5	45–55	Balanced NPK; stimulates microbial activity	Watson, 2022
General frass range (various insects)	1.5–4.0	0.5–2.0	1.0–3.5	40–70	Nutrient-rich, acts as biofertilizer	Abd Manan *et al.*, 2024; Amorim *et al.*, 2024

(IAA), siderophores, and enzymes that improve nutrient uptake and protect plants against soil-borne pathogens (Klammsteiner *et al.*, 2020).

Induced Systemic Resistance (ISR)

A distinctive mechanism associated with insect frass is the induction of systemic resistance in plants. Chitin and its derivatives act as microbe-associated molecular patterns (MAMPs) that are recognized by plant receptors, triggering jasmonic acid and salicylic acid signalling pathways (Sharp, 2013; Poveda *et al.*, 2019). This results in enhanced plant immunity against insect herbivores (e.g., aphids, caterpillars) and pathogens (e.g., *Fusarium*, *Botrytis*). Such plant-mediated defence activation highlights the dual role of frass as both a fertilizer and a biocontrol elicitor.

Suppression of Pests and Pathogens

Frass has been reported to suppress soil-borne diseases and insect pests indirectly. The stimulation of beneficial microbes, production of antimicrobial compounds, and ISR activation reduce the incidence of pathogens such as *Rhizoctonia solani* and *Pythium ultimum* (Quilliam *et al.*, 2020). Moreover, plants grown in frass-amended soils exhibit reduced herbivore performance due to enhanced defence responses and changes in plant secondary metabolites (Poveda *et al.*, 2019). This positions frass as a component of integrated pest management (IPM) strategies.

Improvement of Soil Structure and Ecosystem Functions

Beyond direct nutrient and microbial effects, frass contributes to soil physical improvement by enhancing organic matter content and water retention capacity. This helps maintain soil structure, reduce erosion, and improve resilience against abiotic stresses such as drought (Lalander *et al.*, 2019). Thus, frass functions not only as a nutrient input but also as a soil conditioner that supports long-term soil health.

Comparative Studies: Insect Frass vs. Conventional Fertilizers and Organic Amendments

The potential of insect frass as a biofertilizer has been evaluated against conventional soil amendments such as farmyard manure, compost, vermicompost, and mineral fertilizers. Results from greenhouse and field trials suggest that frass offers competitive, and sometimes superior, agronomic benefits while adding unique properties such as chitin-mediated plant defence.

Frass vs. Compost and Manure

Studies indicate that insect frass can provide comparable or higher nutrient availability than traditional composts and manures. Klammsteiner *et al.*, (2020) reported that black soldier fly (BSF) frass mineralized faster than green waste compost, leading to greater short-term nitrogen availability for crops. Similarly, Houben *et al.*, (2020) demonstrated that frass-amended soils enhanced lettuce biomass production and improved nitrogen use efficiency relative to cattle manure. Unlike compost and manure, frass often has a lower C:N ratio, ensuring quicker nutrient release without significant immobilization.

Frass vs. Vermicompost

Both frass and vermicompost are rich in nutrients and microbial populations; however, frass contains higher levels of chitin, which stimulates soil chitinolytic microbes and induces systemic resistance in plants (Poveda *et al.*, 2019). Vermicompost is generally more effective in improving soil structure and moisture retention, but frass offers additional pest-suppressive properties. In trials with tomato and maize, BSF frass performed on par with vermicompost in enhancing yield, while also reducing incidence of soil-borne diseases (Beesigamukama *et al.*, 2021).

Frass vs. Chemical Fertilizers

While mineral fertilizers provide immediate nutrient availability, they lack the organic matter, microbial

Table 2: Factors affecting frass quality and agronomic value.

Factor	Effect on frass composition	Practical implication	References
Insect species	Determines baseline NPK profile, chitin, and micro bial load	Choose species with higher N for fertilization vs higher chitin for plant defense	Klammsteiner *et al.*, 2020; Houben *et al.*, 2021
Feedstock/ substrate	Nutrient content of feed directly reflected in frass	High-protein feed → higher N; plant-based feed → higher fiber/organic matter	Amorim *et al.*, 2024; Abd Manan *et al.*, 2024
Processing (e.g., drying, composting)	Alters microbial viability, stabilizes nutrients	Composting reduces pathogens, increases humification	De Volder *et al.*, 2025
Storage conditions	Can cause N loss (volatilization), microbial shifts	Store cool, dry, and dark to maintain quality	De Volder *et al.*, 2025
Application rate & method	Determines nutrient release and plant response	Too high → salt stress; optimal ~2–5 t/ha or 2–5% w/w in pot trials	Beesigamukama *et al.*, 2020; Kidd *et al.*, 2025

inoculants, and bioactive compounds present in frass. Beesigamukama *et al.,* (2021) found that maize yields from BSF frass application were comparable to those obtained with mineral fertilizers, but frass-treated soils exhibited better microbial activity and long-term fertility benefits. Moreover, frass contributes to sustainable nutrient cycling by recycling organic waste, unlike synthetic fertilizers that rely on finite resources such as rock phosphate and fossil fuels (Lalander *et al.,* 2019).

Integrated Use of Frass and Other Fertilizers

Some studies highlight the potential of combining frass with compost, manure, or chemical fertilizers for enhanced benefits. For example, partial substitution of mineral fertilizers with frass improved both crop yield and soil microbial activity, offering a balanced approach to sustainable intensification (Quilliam *et al.,* 2020). Such integrated nutrient management strategies may reduce dependency on synthetic inputs while maintaining productivity.

Comparative Limitations

Despite its benefits, frass faces challenges compared to conventional amendments. Nutrient composition of frass can vary significantly depending on insect diet and rearing conditions, whereas chemical fertilizers provide more standardized formulations (Klammsteiner *et al.,* 2020). Additionally, large-scale availability and regulatory approval for agricultural use remain limiting factors for frass commercialization.

Applications of Insect Frass in Agriculture

The agronomic potential of insect frass is being increasingly explored in diverse cropping systems. Its applications span from traditional field crops to controlled-environment agriculture, offering a versatile tool for improving crop productivity, soil health, and resilience against pests and pathogens.

Use in Cereal and Field Crops

Several studies have demonstrated the effectiveness of insect frass in staple crops such as maize, wheat, and rice. For instance, Beesigamukama *et al.,* (2021) reported that BSF frass significantly improved maize biomass, grain yield, and nitrogen use efficiency under field conditions. Similar effects were observed in wheat, where frass application enhanced nutrient uptake and improved root development compared to untreated controls (Houben *et al.,* 2020). The ability of frass to provide slow-release nutrients makes it particularly suitable for cereals with high nutrient demands.

Application in Horticultural Crops

In horticulture, insect frass has shown promise in vegetables, fruits, and ornamentals. Klammsteiner *et al.,* (2020) demonstrated that lettuce grown in BSF frass-amended soil had higher biomass and chlorophyll content compared to compost-treated soils. Tomato plants receiving frass amendments exhibited reduced disease incidence and better fruit quality due to enhanced systemic resistance and microbial interactions (Poveda *et al.,* 2019). These findings suggest that frass could be particularly beneficial for high-value horticultural systems where both yield and quality are critical.

Integration in Nurseries and Controlled Environment Agriculture

In nursery management and hydroponic systems, where rapid nutrient availability and pathogen suppression are crucial, frass has gained attention as a sustainable input. Quilliam *et al.,* (2020) reported that seedlings grown in frass-supplemented substrates developed more vigorous root systems and exhibited reduced damping-off incidence compared to conventional media. In hydroponic settings, processed frass extracts are being tested as organic nutrient solutions, providing a potential alternative to synthetic hydroponic inputs (Yang *et al*., 2021).

Role in Pest and Disease Management

A unique application of insect frass lies in its potential as a plant defense elicitor. The chitin and microbial components in frass stimulate induced systemic resistance, reducing susceptibility to insect herbivores (aphids, caterpillars) and soil-borne pathogens such as Fusarium and Rhizoctonia (Sharp, 2013; Poveda *et al*., 2019). When integrated into Integrated Pest Management (IPM) programs, frass can complement biological control agents (e.g., *Trichoderma*, *Bacillus*) by providing a conducive soil microbiome that suppresses harmful organisms.

Potential in Sustainable and Circular Farming Systems

Insect frass fits well within the circular bioeconomy, where organic residues from food, feed, and waste streams are recycled through insect farming and returned to agriculture as fertilizers. This creates a closed-loop nutrient cycle, reducing dependency on synthetic inputs while promoting sustainability (Lalander *et al*., 2019). Frass application in organic farming systems also holds potential, as it aligns with eco-friendly principles and may qualify for organic certification once regulatory frameworks are standardized.

Challenges and Knowledge Gaps in the Use of Insect Frass

Despite its growing recognition as a sustainable biofertilizer, the large-scale adoption of insect frass in agriculture faces several technical, biological, and regulatory challenges. Addressing these issues is essential to unlock its full potential in commercial crop production.

Variability in Composition

The nutrient content of frass is highly dependent on the insect species, diet, and rearing substrate (Klammsteiner *et al.*, 2020). For example, frass from black soldier fly larvae reared on food waste may differ significantly in nutrient profile from that derived from cereal by-products. This variability complicates its standardization as a fertilizer and may lead to inconsistent agronomic outcomes.

Lack of Standardized Processing and Quality Control

Unlike mineral fertilizers, which have uniform formulations, insect frass lacks standardized production, processing, and storage protocols. Post-harvest handling (drying, pelletizing, sterilization) can influence its microbial composition and nutrient stability (Lalander *et al.*, 2019). Establishing quality standards for moisture content, nutrient concentration, and microbial safety is crucial to ensure reliability and farmer acceptance.

Potential Risks of Pathogens and Contaminants

Frass may carry residual pathogens, heavy metals, or pesticide residues, especially when insects are reared on contaminated substrates (Quilliam *et al*., 2020). Although heat treatment and microbial competition can reduce these risks, comprehensive safety assessments are needed before widespread agricultural use. This is particularly critical for frass intended for food crops consumed raw, such as leafy vegetables.

Limited Field Trials and Long-term Studies

Most studies on frass application are restricted to greenhouse experiments or small-scale trials (Beesigamukama *et al.*, 2021). Large-scale, multi-location field experiments are required to validate its agronomic efficiency across diverse soils, climates, and cropping systems. Furthermore, long-term studies on soil health, carbon sequestration, and pest dynamics under frass amendment are still lacking.

Regulatory and Market Barriers

The commercialization of insect frass is hampered by unclear regulatory frameworks in many countries. While some regions (e.g., EU, North America) have started to include insect-derived products in fertilizer regulations, approval processes remain slow and fragmented (Houben *et al.*, 2020). Additionally, farmer awareness and acceptance are still limited, requiring stronger extension efforts and demonstration trials.

Scalability and Economic Feasibility

Although insect farming is expanding rapidly, the volume of frass generated may still be insufficient to meet large-scale agricultural demand. Moreover, the cost of insect production and frass processing could make it less competitive compared to synthetic fertilizers, unless supported by circular economy incentives or integrated into waste management systems (Lalander *et al.*, 2019).

Future Perspectives

The valorization of insect frass as a biofertilizer is still in its early stages, but ongoing research and technological innovations highlight its potential to become a mainstream agricultural input. Several avenues could enhance its efficiency, scalability, and acceptance in sustainable farming systems.

Standardization and Quality Assurance

Developing international standards for frass composition, safety, and labelling is critical to its commercial success. Nutrient certification, pathogen testing, and microbial profiling should be integrated into regulatory frameworks to ensure farmer confidence and market growth (Houben *et al.*, 2020).

Microbial Fortification and Bio enhancement

Frass could be enriched with beneficial microbes (e.g., *Trichoderma, Bacillus, Rhizobia*) to enhance its biofertilizer and biocontrol potential. Such "designer frass" formulations could deliver nutrients while actively suppressing soil-borne pathogens and pests, providing dual benefits of fertilization and crop protection (Poveda *et al*., 2019).

Nanotechnology and Slow-Release Formulations

Emerging technologies such as nano-fertilizers and controlled-release carriers could be integrated with frass to improve nutrient delivery efficiency and reduce losses through leaching or volatilization. Frass-based nanocomposites may also act as carriers for micronutrients and plant growth regulators, enhancing crop performance under stress conditions.

Integration into Circular Bioeconomy

Frass utilization should be seen as part of a zero-waste insect farming system, where organic waste is converted into insect biomass (feed, food) and frass (fertilizer). Integrating frass into circular nutrient loops can reduce reliance on synthetic fertilizers and lower the environmental footprint of agriculture (Lalander *et al*., 2019). Policy incentives and waste management collaborations will play a key role in scaling such systems.

Applications in Climate-Smart Agriculture

Given its potential to improve soil health, water retention, and resilience against pests, frass could become a valuable component of climate-smart agriculture. Its role in carbon sequestration and greenhouse gas mitigation, though underexplored, represents an exciting research frontier.

Expanding Research Frontiers

Future studies should focus on the following aspects

- Multi-season, large-scale field evaluations across crop systems.
- Long-term impacts on soil microbial diversity, nutrient cycling, and pest dynamics.
- Development of frass-based commercial products (pellets, liquid extracts, microbial inoculant blends).
- Socio-economic studies on farmer perceptions, adoption barriers, and cost–benefit analysis.

Conclusion

Insect frass, once regarded as a by-product of insect farming, is now gaining recognition as a sustainable biofertilizer and soil amendment. Rich in nutrients, organic matter, and beneficial microbes, it offers a promising alternative to synthetic fertilizers. Beyond nutrient supply, frass enhances soil health, promotes plant growth, and provides biocontrol benefits, aligning with sustainable and climate-smart agriculture.

However, challenges such as variability in composition, lack of standardization, safety concerns, and limited field trials hinder its wider use. Regulatory uncertainties and cost-effectiveness also need attention for broader adoption. Future opportunities lie in standardization, microbial fortification, nanotechnology, and integration into the circular bioeconomy. Supportive policies, industry–academia collaborations, and farmer awareness can accelerate its acceptance. Overall, insect frass holds significant potential for reducing chemical fertilizer dependency, improving resource efficiency, and closing nutrient loops in agroecosystems. Its mainstream application will require coordinated or interdisciplinary efforts in research, technology, regulation, and extension.

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