



## **Induction of Plant Defense Responses by Black Soldier Fly (*Hermetia illucens*) Larvae Frass Amendments: A Systematic Review**

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### **Abstract**

Organic soil amendments derived from insect bioconversion systems have emerged as promising tools for sustainable agriculture. Among these, frass produced by larvae of the black soldier fly, *Hermetia illucens*, has attracted increasing scientific attention due to its fertilizing properties and its potential to stimulate plant immune responses. This systematic review synthesizes evidence on the capacity of Black soldier fly larvae frass to induce plant defence mechanisms and improve plant resistance to pathogens and herbivores. Literature was retrieved following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines across major scientific databases including Web of Science, Scopus, PubMed, and Google Scholar. Forty-two studies met the eligibility criteria and were analyzed. Evidence indicates that Black soldier fly larvae frass can activate plant immune pathways associated with Induced Systemic Resistance and Systemic Acquired Resistance, largely mediated through microbial interactions, chitin-derived elicitors, and phytohormonal signalling. Frass amendments also reshape rhizosphere microbial communities, enhance soil fertility, and suppress plant pathogens such as *Ralstonia solanacearum*. However, variability in frass composition, application rates, and experimental conditions limits cross-study comparisons. Further standardized field trials and mechanistic studies are needed to elucidate the molecular pathways underlying frass-mediated plant immunity. This review highlights the emerging role of insect frass as a multifunctional biofertilizer that simultaneously enhances plant growth and defence responses.

**Key words** – induced systemic resistance – insect bioconversion – plant immunity – rhizosphere microbiome

### **Introduction**

The growing demand for sustainable agricultural practices has intensified efforts to identify environmentally friendly alternatives to synthetic fertilizers and pesticides. Conventional agricultural inputs have significantly increased crop yields but have also contributed to soil degradation, nutrient runoff, and environmental pollution (Van Huis 2013, Smetana et al. 2019). Consequently, there is increasing interest in circular bioeconomy strategies that recycle organic waste into valuable agricultural inputs (Kaewchai et al. 2009). One promising technology involves the mass rearing of the black soldier fly, *Hermetia illucens*, whose larvae efficiently convert

organic waste into protein-rich biomass and residual byproducts such as frass (Diener et al. 2011, Akwa et al. 2025). Black soldier fly larvae frass consists of larval excreta, undigested feed residues, microbial biomass, and insect cuticle fragments (Beesigamukama et al. 2020). Traditionally regarded as a waste product, frass is now increasingly recognized as a valuable organic fertilizer due to its nutrient content and beneficial microbial communities.

Recent research has revealed that frass may play a more complex role in plant health beyond nutrient supply. In addition to improving soil fertility, Black soldier fly larvae frass appears capable of stimulating plant defence responses that enhance resistance to pathogens and herbivores (Poveda 2021, Klammsteiner et al. 2020). These responses resemble mechanisms such as induced systemic resistance and systemic acquired resistance, which enable plants to activate defensive pathways following exposure to beneficial microbes or elicitors. Several factors may contribute to the defence-inducing properties of Black soldier fly larvae frass. First, frass contains diverse microbial populations that can function as plant growth promoting rhizobacteria, which are known to stimulate induced systemic resistance (Ray et al. 2016). Second, insect-derived materials present in frass, including chitin from larval exoskeletons, can act as molecular elicitors that activate plant immune signalling pathways (Sharp 2013). Third, frass amendments influence soil microbial community structure, potentially suppressing plant pathogens and promoting beneficial microbes (Menino et al. 2021).

Although the fertilizing properties of insect frass have been widely investigated, its role in plant defence induction remains relatively underexplored. Moreover, the growing expansion of industrial-scale insect farming systems has generated increasing quantities of frass, making it important to understand its potential applications in agriculture. The objective of this study was therefore to conduct a systematic review of the literature addressing the role of Black soldier fly larvae frass in plant defence responses. Specifically, this review aims to: Identify experimental studies evaluating the effects of Black soldier fly larvae frass on plant immunity, summarize the biological mechanisms underlying frass-mediated defence induction, evaluate the impacts of frass on plant disease suppression and pest resistance, identify key research gaps and future directions for this emerging field.

## **Materials & Methods**

### **Review protocol and reporting guidelines**

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines to ensure transparency, reproducibility, and methodological rigor in the literature selection process (Moher et al. 2009, Page et al. 2021). The review protocol defined the research objectives, eligibility criteria, literature search strategy, and methods for data extraction and synthesis prior to the start of the study. The review aimed to identify experimental studies evaluating the effects of frass produced by larvae of the *Hermetia illucens* on plant defense responses, disease suppression, and rhizosphere microbial interactions. Particular emphasis was placed on studies investigating plant immune signaling pathways such as induced systemic resistance and systemic acquired resistance.

### **Literature search strategy**

A comprehensive literature search was performed across four major scientific databases to identify relevant peer-reviewed publications: Web of Science Core Collection, Scopus, PubMed and Google Scholar. The search covered publications from January 2000 to February 2026, reflecting the period during which research on insect frass and black soldier fly bioconversion has rapidly expanded (Van Huis 2013, Smetana et al. 2019). Search queries were constructed using Boolean operators and combinations of keywords related to insect frass and plant defense responses. Additional searches were performed using related terms such as: “insect frass fertilizer”, “Black soldier fly larvae frass soil amendment”, “insect bioconversion fertilizer”, “plant growth promoting microbes in frass”. Reference lists of relevant articles and review papers were

also manually screened to identify additional studies that may not have appeared in the database search.

### **Study eligibility criteria**

Studies were selected according to predefined inclusion and exclusion criteria.

### **Inclusion criteria**

Publications were included if they met the following criteria:

1. The study investigated frass produced by larvae of the *Hermetia illucens*.
2. The research evaluated plant responses following frass application.
3. Experimental data were reported from greenhouse, laboratory, or field trials.
4. Outcomes included plant growth responses, plant defense responses, rhizosphere microbial changes, or disease suppression.
5. The study was published in a peer-reviewed scientific journal.
6. The article was written in English.

### **Exclusion criteria**

Studies were excluded if they:

1. Focused exclusively on insect rearing or waste bioconversion without plant experiments
2. Examined frass from other insect species.
3. Reported only chemical characterization of frass without plant trials.
4. Were conference abstracts, editorials, or review papers without primary experimental data.

### **Study selection process**

All records identified from the database search were imported into reference management software (Zotero) to facilitate screening and removal of duplicate entries. The study selection process consisted of four sequential stages consistent with Preferred Reporting Items for Systematic Reviews and Meta-Analyses methodology (Fig 1):

1. Identification – The initial database search yielded 1,248 records. Duplicate records were removed using automated detection and manual verification.
2. Screening – Following duplicate removal, 982 articles remained for title and abstract screening. Articles were screened to determine whether they addressed insect frass, plant responses, or soil amendments.
3. Eligibility assessment – A total of 97 full-text articles were retrieved and assessed in detail to determine whether they met the eligibility criteria.
4. Inclusion – After full-text evaluation, 42 studies were selected for inclusion in the qualitative synthesis.

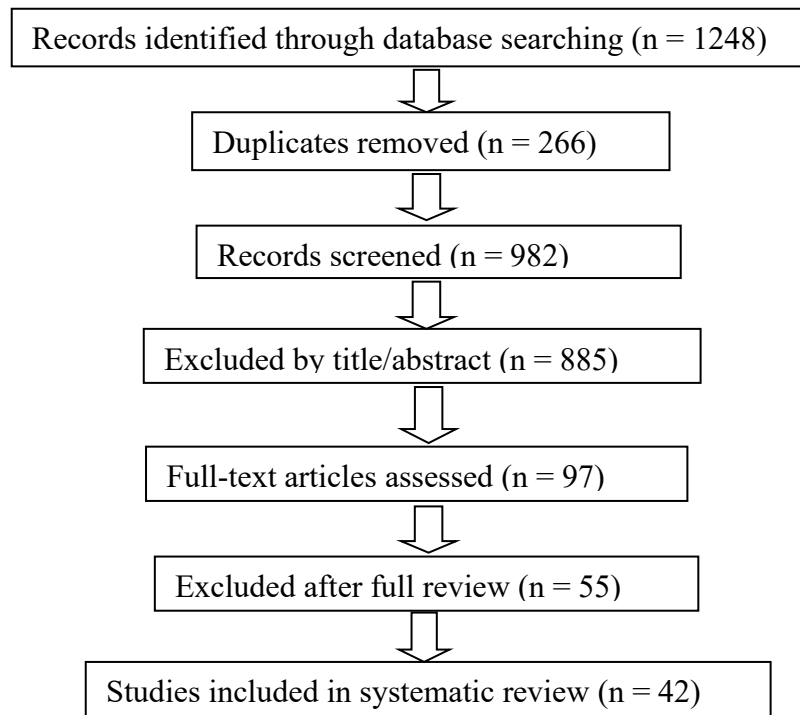
### **Data extraction**

Data from each included study were extracted systematically using a standardized data extraction sheet. The following information was recorded: Study characteristics, authors and year of publication, country or geographic region of the study, experimental setting (greenhouse, field trial, laboratory), Frass characteristics, larval feed substrate used for rearing, frass processing method (fresh, composted, dried), reported nutrient composition (Nitrogen, Phosphorus, Potassium), microbial characterization (if available), Plant experimental parameters, plant species and cultivar tested, soil type or growth medium, frass application method (soil amendment, extract, or top dressing), application rate or concentration. Data extraction was conducted independently by the reviewer and cross-checked for consistency.

### **Quality assessment of included studies**

To evaluate the methodological reliability of the included studies, a qualitative quality assessment was performed based on criteria adapted from systematic review methodologies used in

agricultural research (Haddaway et al. 2015). Each study was evaluated based on the following criteria: clarity of experimental design, replication and sample size, description of frass composition or source, statistical analysis methods, reporting of plant response variables. Studies were categorized as high, moderate, or low methodological quality based on the completeness of methodological reporting and experimental rigor.



**Fig 1.** – Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram for selection process

### Data synthesis and analysis

Due to the heterogeneity of experimental designs, plant species, and outcome variables across the selected studies, a quantitative meta-analysis was not feasible. Instead, a qualitative narrative synthesis approach was adopted. Studies were grouped according to the following thematic categories: Frass nutrient composition and soil fertility effects, rhizosphere microbial interactions, plant growth promotion, plant defense induction mechanisms, disease and pest suppression outcomes. Patterns and trends across studies were analyzed to identify common mechanisms through which Black soldier fly larvae frass influences plant health and immunity.

## Results

### Overview of included studies

A total of 42 studies met the inclusion criteria and were included in the qualitative synthesis. These studies evaluated the effects of frass produced by larvae of the *Hermetia illucens* on plant growth, soil microbial dynamics, and plant defense responses. Most studies were published within the last decade, reflecting the growing scientific interest in insect-based agricultural inputs (Smetana et al. 2019, Poveda 2021). The majority of the experiments were conducted under controlled greenhouse or pot conditions, while fewer studies examined field-scale applications. Across the included studies, Black soldier fly larvae frass was primarily used as a soil amendment, although several experiments evaluated frass extracts, composted frass, or liquid frass-based fertilizers. The crops investigated included both horticultural and field crops, with tomato, lettuce,

maize, wheat, and cucumber being the most frequently studied species (Beesigamukama et al. 2020, Menino et al. 2021).

### Geographic distribution of studies

The geographic distribution of research on Black soldier fly larvae frass reflects the global expansion of insect farming systems (table 1). Most studies originated from Europe and Asia, followed by North America and Africa. European studies often focused on waste bioconversion and soil fertility, while Asian studies frequently examined agricultural productivity and disease suppression. The geographic spread highlights the increasing global interest in insect-derived fertilizers as part of sustainable agricultural systems.

**Table 1** Geographic distribution of studies included in the review

Region	Number of studies	Percentage
Europe	16	38%
Asia	12	29%
North America	7	17%
Africa	5	12%
South America	2	4%

### Crop species investigated

The studies reviewed investigated a wide range of crop species across different agricultural systems. Tomato was the most frequently studied crop due to its susceptibility to soil-borne pathogens and its common use in plant pathology experiments (Menino et al. 2021).

**Table 2** Crop species investigated in studies evaluating Black soldier fly larvae frass

Crop species	Number of studies	Experimental context
Tomato	11	Disease suppression, plant growth
Lettuce	8	Soil fertility and yield
Maize	7	Nutrient uptake and biomass
Wheat	5	Rhizosphere microbial activity
Cucumber	4	Plant growth promotion
Soybean	3	Nutrient availability
Other crops	4	Various horticultural crops

**Table 3** Typical nutrient composition of Black soldier fly larvae frass reported in studies

Nutrient	Typical concentration range
Nitrogen (N)	2–5%
Phosphorus (P)	1–3%
Potassium (K)	1–4%
Organic matter	40–60%
Carbon:N ratio	10–20

These nutrient concentrations contribute to the fertilizing effect of frass and explain the growth-promoting responses observed in many studies (Beesigamukama et al. 2020, Lalander et al. 2019).

However, frass composition was strongly influenced by the diet used to rear larvae, which included food waste, manure, crop residues, and agro-industrial byproducts.

### Frass composition and nutrient characteristics

Several studies reported the chemical composition of Black soldier fly larvae frass. Although nutrient content varied depending on larval feed substrates, most studies identified frass as a nutrient-rich organic fertilizer containing: nitrogen (N), phosphorus (P), potassium (K), organic carbon and micronutrients (table 3)

### Effects of Black soldier fly larvae frass on plant growth

The majority of studies included in this review reported positive plant growth responses following frass application (table 4). Commonly observed effects included: increased plant height, greater root biomass, improved leaf chlorophyll content and higher crop yields.

**Table 4** Reported plant growth responses to Black soldier fly larvae frass

Study	Crop	Experimental system	Growth response
Beesigamukama et al. 2020	Maize	Field trial	Increased biomass and yield
Menino et al. 2021	Tomato	Greenhouse	Higher plant biomass
Klammsteiner et al. 2020	Lettuce	Pot experiment	Increased leaf area
Lalander et al. 2019	Various crops	Greenhouse	Enhanced growth rates
Choi et al. 2009	Cabbage	Greenhouse	Increased plant height

The positive effects observed in these studies are attributed to both nutrient supply and microbial activity associated with frass amendments.

### Effects on rhizosphere microbial communities

Several studies reported that frass amendments significantly altered soil microbial communities (table 5). The microbial populations associated with frass often include bacteria with plant growth promoting properties such as: *Bacillus* species, *Pseudomonas* species and *Enterococcus* species. These microbes can contribute to plant health by improving nutrient availability and suppressing plant pathogens (Klammsteiner et al. 2020). The presence of these microbial communities suggests that frass may function not only as a fertilizer but also as a microbial inoculant for soil ecosystems.

**Table 5** Microbial taxa frequently detected in Black soldier fly larvae frass

Microbial group	Reported function
<i>Bacillus spp.</i>	Plant growth promotion, pathogen suppression
<i>Pseudomonas spp.</i>	Induced systemic resistance
<i>Enterococcus spp.</i>	Nutrient cycling
<i>Actinomycetes</i>	Antibiotic production

### Induction of plant defense responses

A subset of the reviewed studies investigated plant defense responses following frass application. These responses included: increased activity of defense-related enzymes, enhanced expression of plant immune genes, reduced disease severity following pathogen infection. Several mechanisms were proposed to explain these effects. First, beneficial microbes in frass may stimulate induced systemic resistance, a defense mechanism activated by plant growth-promoting rhizobacteria (Ray et al. 2016). Second, frass contains chitin fragments derived from insect exoskeletons. Chitin is recognized by plant immune receptors and can trigger defense responses

(Sharp 2013). Third, frass application may influence plant hormonal pathways involved in immune signaling, including the jasmonic acid and salicylic acid pathways (Poveda 2021).

### Effects on plant disease suppression

Several studies reported that frass amendments reduced the incidence or severity of plant diseases (table 6). Disease suppression may occur through multiple mechanisms including microbial competition, antimicrobial compound production, and activation of plant immune responses.

**Table 6** Examples of disease suppression following Black soldier fly larvae frass application

Study	Crop	Pathogen	Observed effect
Menino et al. 2021	Tomato	<i>Ralstonia solanacearum</i>	Reduced bacterial wilt severity
Poveda 2021	Tomato	Soil-borne pathogens	Improved plant resistance
Ray et al. 2016	Wheat	Fungal pathogens	Lower infection rates

## Discussion

### Overview of the role of Black soldier fly larvae frass in plant health

This systematic review synthesized evidence from 42 studies examining the agricultural effects of frass produced by larvae of the *Hermetia illucens*. Black soldier fly larvae frass functions not only as an organic fertilizer but also as a potential biological stimulant capable of influencing plant growth, soil microbial communities, and plant defence responses. Most studies included in this review reported improvements in plant growth following frass application. Increased plant biomass, improved nutrient uptake, and enhanced yield were consistently observed across several crop species, including tomato, lettuce, maize, and wheat (Beesigamukama et al. 2020, Menino et al. 2021). These results confirm earlier findings that insect frass can serve as an effective organic fertilizer due to its relatively high nutrient content and favorable carbon-to-nitrogen ratio (Lalander et al. 2019). However, beyond nutrient supply, several studies suggest that Black soldier fly larvae frass may also stimulate plant defence mechanisms. Evidence from rhizosphere microbiology, plant physiology, and disease suppression experiments indicates that frass amendments can influence plant immunity through a combination of microbial, biochemical, and physiological mechanisms.

### Nutrient-mediated growth promotion and plant vigor

The most direct effect of frass application observed across studies was improved plant growth. This outcome can largely be explained by the nutrient composition of frass, which typically contains moderate concentrations of nitrogen, phosphorus, and potassium (Beesigamukama et al. 2020). Organic fertilizers improve plant growth through both nutrient availability and soil structural improvements. Frass contains significant amounts of organic matter that enhance soil water retention, microbial activity, and nutrient cycling processes. These properties can improve root development and increase plant access to essential nutrients (Smetana et al. 2019). The positive effects on plant vigor may indirectly contribute to improved plant resistance to pathogens. Healthy plants with adequate nutrient supply often exhibit stronger defence responses compared with nutrient-stressed plants (Ray et al. 2016). Therefore, part of the disease suppression observed in frass-amended soils may result from improved plant physiological condition. Nevertheless, nutrient supply alone cannot fully explain the defence-related effects observed in several studies, suggesting that additional mechanisms are involved.

### Role of rhizosphere microbiota in frass-mediated plant defence

One of the most significant findings across studies was the strong influence of Black soldier fly larvae frass on soil microbial communities. Frass is not a sterile material; it contains a diverse

microbiome originating from larval gut microorganisms, feed substrate microbes, and environmental microbial populations (Klammsteiner et al. 2020). Several bacterial genera frequently identified in frass, including *Bacillus*, *Pseudomonas*, and *Enterococcus*, are plant growth-promoting rhizobacteria. These microbes can enhance plant health through various mechanisms, including nutrient solubilization, phytohormone production, and pathogen suppression (Ray et al. 2016). plant growth promoting rhizobacteria are also known to activate induced systemic resistance, a plant defence mechanism that enhances resistance to pathogens without directly triggering a strong immune response. Instead, induced systemic resistance primes plants to respond more rapidly and effectively when pathogen attack occurs. Studies included in this review reported increased microbial diversity and shifts in rhizosphere bacterial communities following frass application (Klammsteiner et al. 2020, Menino et al. 2021). These changes may create a more competitive microbial environment that suppresses soil-borne pathogens. Furthermore, microbial metabolites produced by frass-associated microbes may directly inhibit pathogens or stimulate plant defence signalling pathways. For example, some *Bacillus* species produce antibiotics and lipopeptides that suppress fungal pathogens in the rhizosphere. Therefore, the microbiological component of frass likely plays a central role in mediating plant defence responses.

### **Chitin-mediated activation of plant immune responses**

Another mechanism contributing to plant defence induction is the presence of chitin fragments derived from insect exoskeletons. During the development of larvae of the *Hermetia illucens*, molting and degradation processes generate chitin-rich residues that accumulate in frass. Chitin is recognized by plant pattern-recognition receptors and functions as a microbe-associated molecular pattern capable of activating plant immune responses (Sharp 2013). When plants detect chitin molecules, they initiate defence signalling pathways that include: reactive oxygen species production, activation of defence-related genes and reinforcement of plant cell walls. These responses can increase plant resistance to fungal pathogens and certain insect pests. Several studies have demonstrated that chitin-containing soil amendments stimulate plant defence enzymes such as chitinases and peroxidases (Sharp 2013). Because frass naturally contains chitin, it may function as a biological elicitor capable of priming plant immunity. This mechanism is particularly relevant for fungal disease suppression, as many fungal pathogens rely on chitin-containing cell walls.

### **Hormonal signalling pathways involved in frass-induced immunity**

Plant defence responses are regulated by complex hormonal signalling networks. Two major pathways involved in plant immunity are mediated by salicylic acid and jasmonic acid. Salicylic acid signalling is typically associated with resistance to biotrophic pathogens, while jasmonic acid signalling plays a major role in defence against herbivorous insects and necrotrophic pathogens (Poveda 2021). Evidence suggests that frass amendments may influence these hormonal pathways through microbial interactions or biochemical elicitors. For example, plant growth promoting rhizobacteria are known to activate jasmonic acid-dependent defence responses, leading to induced systemic resistance. Although only a limited number of studies directly measured plant hormone responses following frass application, available evidence suggests that both salicylic acid and jasmonic acid pathways may be involved. Further research using transcriptomic and metabolomic approaches will be necessary to fully characterize the molecular signalling pathways activated by frass amendments.

### **Evidence for disease suppression**

Several studies included in this review reported reduced disease severity in plants grown in frass-amended soils. For example, experiments with tomato plants demonstrated reduced incidence of bacterial wilt caused by *Ralstonia solanacearum* following frass application (Menino et al. 2021).

Disease suppression may occur through multiple mechanisms:

1. Competition between beneficial microbes and pathogens in the rhizosphere.
2. Production of antimicrobial metabolites.
3. Activation of plant immune responses.
4. Improved plant vigor due to enhanced nutrient availability.

It is likely that these mechanisms operate simultaneously, creating a complex network of interactions that enhance plant resilience. However, relatively few studies have conducted controlled pathogen challenge experiments. Consequently, further research is needed to confirm the reliability of frass as a biological disease management strategy.

### **Implications for circular agriculture and sustainable farming**

The increasing global expansion of insect farming systems presents an opportunity to integrate insect-derived byproducts into sustainable agricultural practices. Frass generated during the production of larvae of *Hermetia illucens* represents a valuable resource that can contribute to circular agricultural systems by recycling nutrients from organic waste streams. Utilizing frass as a biofertilizer can reduce dependence on synthetic fertilizers and support soil health by promoting microbial diversity and organic matter accumulation (Smetana et al. 2019). Furthermore, if frass-mediated plant defence induction can be reliably demonstrated, frass could serve as a multifunctional agricultural input combining fertilization and biological plant protection. This dual functionality could be particularly valuable for organic farming systems and low-input agricultural practices.

### **Future research directions**

Although the results of this review highlight the potential of Black soldier fly larvae frass as a plant defence stimulant, several key research gaps remain.

Future studies should focus on:

1. Standardizing frass characterization methods to allow comparison across experiments.
2. Conducting large-scale field trials to validate greenhouse findings.
3. Investigating plant immune signalling pathways using molecular approaches such as transcriptomics and metabolomics.
4. Characterizing frass microbiomes to identify key microbial taxa responsible for plant defence induction.
5. Exploring interactions between frass amendments and biological pest control agents.

Addressing these research priorities will be essential for developing optimized frass-based fertilizers and plant health products.

### **Conclusions, Limitations and Recommendations**

This systematic review synthesizes the current body of literature evaluating the role of black soldier fly larvae frass as a soil amendment capable of inducing plant defence responses. Across multiple experimental systems, evidence consistently demonstrates that Black soldier fly larvae frass functions not merely as an organic fertilizer but also as a biologically active amendment that can enhance plant resilience to biotic stress. The studies reviewed reveal that frass-mediated effects arise through several complementary mechanisms, including nutrient enrichment, microbiome-mediated plant growth promotion, and the activation of plant immune signalling pathways. One of the most consistent findings across the literature is that Black soldier fly larvae frass improves plant growth and productivity while simultaneously enhancing plant defensive capacity. The frass typically contains substantial quantities of nitrogen, phosphorus, potassium, and organic carbon, making it a valuable fertilizer substitute. However, beyond these nutritional benefits, the biological constituents of frass appear to play a central role in triggering plant defence responses. Microbial communities associated with frass often include plant growth-promoting rhizobacteria, such as species within the genera *Bacillus*, *Pseudomonas*, and *Enterococcus*. These microorganisms are known to stimulate systemic resistance in plants, thereby reducing susceptibility to pathogens and

herbivorous insects. In addition to microbial components, frass contains biologically active molecules derived from insect digestion processes. Compounds such as chitin fragments, antimicrobial peptides, and residual metabolites may act as elicitors of plant immune responses. Chitin and its derivatives, in particular, are widely recognized as microbe-associated molecular patterns capable of triggering pattern-triggered immunity in plants. Exposure to these compounds can stimulate signalling pathways involving jasmonic acid, salicylic acid, and ethylene, which regulate defence-related gene expression. Consequently, plants grown in frass-amended soils often exhibit increased levels of defence enzymes such as peroxidases, polyphenol oxidases, and phenylalanine ammonia-lyase. The literature further suggests that Black soldier fly larvae frass may contribute to enhanced resistance against both pathogens and insect pests.

Despite the promising results documented across the reviewed studies, the current evidence base remains relatively limited in scale and scope. Many studies were conducted under controlled greenhouse conditions rather than in field environments, and the diversity of crop species examined remains narrow. Furthermore, considerable variation exists in frass composition due to differences in larval diet, rearing conditions, and post-harvest processing. These factors can significantly influence the chemical and microbial characteristics of frass, potentially affecting its agronomic performance. Standardization of frass characterization protocols would therefore enhance comparability across studies and facilitate more robust meta-analytical evaluations in the future.

Another important research gap concerns the precise molecular mechanisms underlying frass-induced plant defence responses. While several studies have documented increases in defence-related enzymes or gene expression, comprehensive transcriptomic and metabolomic analyses remain scarce. Future research should aim to elucidate the signalling pathways involved in frass-mediated immune activation, particularly in relation to the jasmonic acid and salicylic acid pathways that regulate plant responses to herbivores and pathogens. Such mechanistic insights would not only strengthen our understanding of frass-plant interactions but also support the development of optimized application strategies.

Future studies should also investigate optimal application rates, timing, and integration with other soil management practices. For example, combining frass with compost, biochar, or microbial inoculants may enhance its effectiveness as a plant defence stimulator. Likewise, exploring the interactions between frass amendments and crop genotype could reveal whether certain cultivars respond more strongly to frass-induced defence priming.

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