



Comparison of black soldier fly *Hermetia illucens* (Diptera: Stratiomyidae) frass to chemical and organic fertilizers on arthropod abundance and edamame plant performance

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Abstract

The use of *Hermetia illucens* L. (Diptera: Stratiomyidae) larvae for the bioconversion of organic waste into protein and frass is gaining popularity. Although frass of *H. illucens* has been proposed as an organic fertilizer, its relative impact on crop productivity and soil organism diversity remains insufficiently understood compared to other fertilizers. We, therefore, evaluated the effectiveness of frass of *H. illucens* relative to commercial chemical (NPK) fertilizer and compost in edamame (*Glycine max* (L.) Merr.) production while also considering their potential within the circular economy framework. Edamame plants in NPK plots averaged 71.1 ± 0.79 cm in height, which was not significantly different from frass of *H. illucens* plots at 69.47 ± 3.22 cm ($p > 0.05$). The frass of *H. illucens* plots also had the highest average yield (84.27 ± 8.79 g/plant), which did not differ significantly from NPK plots (85.05 ± 7.37 g/plant) ($p > 0.05$). In addition, the application of frass of *H. illucens* increased the abundance of soil arthropods (5.62 ± 0.99 individuals/plot), exceeding all other treatments ($p < 0.05$). Predators were especially abundant in frass of *H. illucens* plots (3.87 ± 0.91 individuals/plot) compared to other treatments ($p < 0.05$). Ground beetles (Coleoptera) were the dominant arthropod group across all treatments. Conversely, foliar arthropod abundance was significantly affected by fertilizer type, with frass of *H. illucens* demonstrating the highest increase across trophic levels ($p < 0.05$). Overall, our findings indicate that frass of *H. illucens* not only enhances edamame plant growth and yield but also fosters greater soil and foliar arthropod abundance. By recycling organic waste into a valuable agricultural input, frass of *H. illucens* contributes to improved biodiversity and aligns with circular economy principles, offering a more sustainable approach to crop production.

Keywords Black soldier fly · Circular economy · Edamame · Insect frass · Sustainability

Introduction

Sustainable agriculture has become a global priority in response to growing environmental concerns, resource limitations, and the need for long-term food security. As conventional farming practices often rely heavily on synthetic inputs, there is increasing interest in natural alternatives that can maintain productivity while minimizing ecological impact. In this context, insect-derived fertilizers, particularly insect frass, have gained attention for their potential to bridge the gap between sustainability goals and practical nutrient management. Insect frass, a by-product of insect rearing, is rich in essential nutrients such as nitrogen, phosphorus, potassium, calcium, and micronutrients in adequate ratios to support overall plant nutrition (Fischer

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et al. 2021; Houben et al. 2020; Kagata and Ohgushi 2012; Klammsteiner et al. 2020), and also contains beneficial micro-organisms that enhance plant growth and improve soil health (Poveda 2021). Its dual role as both a nutrient source and soil biological enhancer positions insect frass as a promising input for more sustainable farming systems.

Research interest in insect frass, particularly *Hermetia illucens* L. (Diptera: Stratiomyidae) frass, is growing in many countries. Frass of *H. illucens*, a by-product of black soldier fly larvae, is an invaluable organic fertilizer that supports circular economies and environmentally friendly practices while promotes plant growth (Lomonaco et al. 2024). Several studies have demonstrated the successful application of frass of *H. illucens* on various crops, including lettuce (Borkent and Hodge 2021; Chiam et al. 2021), herbs (Borkent and Hodge 2021), pakchoi (Song et al. 2021), and maize (Beesigamukama et al. 2020b; Tanga et al. 2022). In particular frass of *H. illucens* enhances plant performance through various pathways, including interactions with the root system, soil, and overall plant physiology (Chavez et al. 2024; Yudistira et al. 2025; Elissen et al. 2023; Gurung et al. 2024).

The precise mechanisms may vary depending on the specific plant species and environmental conditions. Frass of *H. illucens*, as an organic fertilizer, typically provides a slow-release mechanism of nutrients. This gradual release aligns with plant growth phases, thereby minimizing nutrient leaching and ensuring a sustained nutrient supply (Fischer et al. 2021), which may improve nutrient uptake efficiency (Beesigamukama et al. 2020a). Interestingly, Klammsteiner et al. (2020) reported that frass of *H. illucens* produced plant growth comparable to that of ammonium nitrate (NH_4NO_3), suggesting that a portion of the nitrogen in frass may be available in readily mineralizable forms. This apparent discrepancy may be due to variations in frass composition, such as the presence of soluble ammonium, or environmental factors such as soil type, moisture, or microbial activity that can accelerate nutrient mineralization. In addition, the organic matter in frass of *H. illucens* improves soil structure by increasing porosity, water retention, and aeration, thus creating favorable conditions for root development and microbial activity (Gebremikael et al. 2022; Rehan et al. 2024).

The application of frass of *H. illucens* may also enhance microbial activity in the soil (Beesigamukama et al. 2020a, b; Watson et al. 2021). According to Gebremikael et al. (2022) frass of *H. illucens* could increase microbial activity, biomass, and diversity, including mycorrhizal fungi and nitrogen-fixing bacteria. This is supported by Watson et al. (2021), who showed that frass of *H. illucens* application led to an increase in microbial biomass. An increase in microbial activity benefits soil arthropods, such as collembolans and isopods, contributing to the overall biodiversity in the soil ecosystem

(Teuben and Roelofsma 1990; Carter and Noronha 2007). The application of frass of *H. illucens* may contribute to enhanced plant performance due to improved nitrogen availability, which in turn can influence arthropod diversity. Increased nitrogen uptake may stimulate vegetative growth and improve food quality for plant-feeding insects, such as aphids and leafhoppers, which are known to respond positively to nitrogen-enriched hosts (Rostami et al. 2012; Virila et al. 2023). The frass of *H. illucens* application may also attract beneficial predators such as ground beetles, spiders, ladybugs, or parasitoids because of the increase in herbivores or detritivores in the field (Virila et al. 2023). Unlike conventional fertilizers, frass of *H. illucens* also contains chitin and a rich microbial community that may induce systemic resistance and alter soil food web dynamics (Anedo et al. 2025; Kisaakye et al. 2024), offering additional ecological benefits beyond nutrient provision.

Based on this background, frass of *H. illucens* presents numerous advantages, ranging from improvements in soil fertility and structure to broader ecological impacts. Over-reliance on chemical fertilizers has been associated with soil degradation, microbial decline, acidification, nutrient runoff, and long-term unsustainability (Ning et al. 2017; Wang et al. 2023). By contrast, using of frass *H. illucens* as an organic fertilizer may reduce the demand for synthetic inputs, foster more resilient soil and insect communities, and ultimately support sustainable agroecosystems (Agustiyani et al. 2021; Chiam et al. 2021; Song et al. 2021). Moreover, by minimizing chemical exposure, frass of *H. illucens* could provide a more favorable environment for arthropod biodiversity (Jat et al. 2022). Nevertheless, its effectiveness is influenced by factors, such as application rate, crop type, and soil characteristics (Chavez et al. 2024; Borkent and Hodge 2021; Yudistira et al. 2025). Therefore, this study aimed to evaluate the effects of frass from *H. illucens* compared with chemical and commercial organic fertilizers on the growth and yield of the local soybean ‘dadachamame’, as well as on the abundance of soil and foliar arthropods in the field.

Methods

Farm preparation and transplanting

This research was conducted at the experimental farm of the faculty of agriculture, Yamagata University, in Tsuruoka, Japan, from June to September 2023. In this study, the local variety “Edamame” (cv. ‘Shirayama’) was used. Seedlings were raised in a greenhouse using seed trays, with commercial seedling soil serving as the growth medium. The experimental field measured 13 m × 11.2 m and was divided into

plots measuring 1.2 m × 1.8 m. Soil cultivation was carried out 2 weeks before planting using a hand tractor. Each planting hole received a single seedling approximately 14 days. The planting distance was maintained at 50 cm × 50 cm.

Insect colony preparation

Black soldier flies (*Hermetia illucens*) were reared in a climate-controlled room (22–25 °C; 70–75% RH) with secured access. Larvae were maintained in 14-L plastic containers at densities of 1500–2000 larvae per bin. Each bin was provided with homogenized feed at a rate of approximately 175 mg larva⁻¹ day⁻¹, corresponding to a total of 3.7–4.9 kg over a 14 day rearing period. The feed consisted of a homogenized mixture of food waste and vegetables at a 1:2 (w/w) ratio. Pupae were transferred to moist grounded coffee for pupation, and adults were housed at cage with 200 individuals per cage to encourage oviposition. Adults were supplied with a honey diet and ad libitum water via sponges and misting. A 12:12 light:dark cycle was maintained using specific lights. Handling was minimized, with larvae and adults managed gently by hand. Escaped adults were recaptured using a long-handled insect net.

Frass preparation

Food waste was collected from the Yamagata University Co-op “Vert” convenience store and Tsuruoka Municipal Shonai Hospital, consisting of noodles, rice boxes (with meat, chicken, and eggs), rice balls, bread, and vegetables. Nutrient composition of each item was determined from product labels or published nutrient databases (Table S1). All waste was manually sorted to remove packaging and contaminants, then blended into a homogeneous consistency using a commercial food processor. Black soldier fly larvae, 5–7 days and obtained from the insect colony, were introduced into the containers and reared for 14 days under climate-controlled condition.

At the end of the feeding phase, prepupae and residual material were separated with a 1 mm sieve, leaving frass composed of larval exuviae and chitin-rich residues. Frass composition was analyzed for carbon-to-nitrogen (C/N) ratio, total nitrogen (TN), and total carbon (TC) using a Sumigraph NC-220 F analyzer (Sumika Chemical Analysis Service, Ltd., Tokyo, Japan), total phosphorus (P) by the vanadomolybdophosphoric acid colorimetric method (Kuo and Sparks 1996), and total potassium (K) by atomic absorption spectrometry (Mizuno 1980) (Table 1).

Fertilizer application

The study consisted of four treatments: Frass of *H. illucens*, NPK 8–8–8 (Akagi Gardening Co., Ltd., Isesaki, Japan),

Table 1 Chemical properties of fertilizer

Chemical properties	Frass of <i>H. illucens</i>	Commercial compost	NPK
Total N (%)	4.16	0.7	8
Total P (%)	8.70	0.5	8
Total K (%)	4.80	0.8	8
Total C (%)	30.88	36	0

commercial compost (Forex mori Co., Ltd, Hokkaido, Japan), and a control with no fertilizer (Table 1). The application rates were 540 g/plot for frass of *H. illucens*, 281 g/plot for NPK, and 3208 g/plot for commercial compost, all equivalent to 104 kg N/ha. Each treatment was replicated 4 times. Fertilizers were applied 1 week prior to transplanting and evenly distributed across the experimental plots.

Plant analysis

Edamame plant performance was assessed in plots from randomly selected plants. Edamame plant characteristics included plant height (cm), number of leaves, and leaf color. The plant performance parameters were recorded once per week until the end of the vegetative phase. The leaf color (i.e., leaf greenness) was measured using a soil plant analysis development device (SPAD-502Plus, Konica Minolta, Tokyo, Japan) or known as SPAD value. Additional parameters, including yield, number of pods, and number of empty pods, were recorded after harvest.

Soil arthropod collecting

Soil arthropods were sampled using pitfall traps made from 545 mL plastic cups (CP92-545, Daiso Industries Co., Ltd., Higashi Hiroshima, Japan). Each trap was filled with 200 mL of water and 1 mL of dish detergent to instantly kill the captured arthropods. Each trap was mounted on a pole and placed between adjacent plants at 07:00 a.m., then collected after 24 h. Pitfall traps were deployed in July and August. This study focused on macro-arthropods due to their significant impact on pest dynamics. The total number of arthropods captured in the traps was counted and identified using a Nikon C-PS stereo microscope (SMZ800, Nikon Solutions Co., Ltd., Tokyo, Japan) at the applied ecology laboratory, Yamagata University. Arthropods were classified and categorized according to their feeding group.

Foliar arthropod collecting

The foliar arthropods were collected using yellow sticky traps (Holiver, Arista Life Sciences, Tokyo, Japan) (10 cm × 10 cm). The traps were mounted on poles 50 cm

above the soil surface. In each plot, only a single trap was placed between plants the collection was set up at 08:00 am for 24 h. Collected arthropods were examined under a Nikon C-PS stereo microscope and identified to the genus level. Arthropods were identified to the morpho-genus level based on standard taxonomic references, including Higley and Boethel (1994) and Borror et al. (1996), and subsequently categorized according to their feeding guilds.

Plant damage

Insect pest damage was assessed based on foliar damage. Five plants per plot were sampled weekly to evaluate pest damage, starting from the first week and continuing until the fourth week after treatment application. Damage was rated on a scale of 0 to 5, where 0=no damage (0%), 1=slight damage (1–10%), 2=moderate damage (11–25%), 3=considerable damage (26–50%), 4=severe damage (51–75%), and 5=extreme damage (76–100%), following the method described by Burks and Brandl (2005).

Statistical analysis

All statistical analyses were conducted using R version 4.2.1. Before conducting the analysis, the normality of the data was tested using the Shapiro–Wilk test ($p > 0.05$) to confirm they followed a normal distribution. Plant performance parameters, yield, and plant damage were assessed with a one-way analysis of variance (ANOVA), followed by Tukey's test. The abundance of soil and foliar arthropods was evaluated using a likelihood ratio (LR) test within a generalized linear model (GLM). The GLM employed a Poisson error distribution. Deviance was assessed using the chi-square test. Non-metric multidimensional scaling (NMDS) was employed for visualizing assemblage composition, utilizing the “vegan” package and based on a matrix of Bray–Curtis dissimilarities of abundance data (square root transformed). An analysis of similarities (ANOSIM) with 999 permutations was

applied to the Bray–Curtis matrix to test the null hypothesis of no difference in species composition among treatments. A principal component analysis (PCA) was used to analyze the effect of treatment on arthropod abundance, plant damage, and number of leaves. “FactoMineR” and “factoextra” packages were utilized for the PCA.

Results

Effect of different fertilizer types on the plant

Plant performance

The study assessed the impact of different fertilizers (frass of *H. illucens*, NPK, Compost, and Control) on edamame plant performance, focusing on plant height, number of leaves, SPAD values, yield, and pod count. As shown in Table 2, NPK treatment produced the tallest plants at 71.1 ± 0.79 cm, which was 19.7% taller than the control (59.40 ± 2.14 cm), followed by *H. illucens*-treated plants were 69.47 ± 3.22 cm (17.0% taller) and compost-treated plants were 63.95 ± 2.21 cm (7.7% taller). Plant heights differed significantly among treatments ($df = 3$, $F = 5.58$, $p < 0.05$).

Frass of *H. illucens*-treated plants had 17.85 ± 3.24 leaves per plant (32.7% more than the control), NPK-treated plants had 17.30 ± 1.08 leaves per plant (28.7% more), and compost-treated plants had 16.90 ± 1.72 leaves per plant, while the control had 13.45 ± 0.85 leaves per plant, with no statistical significance in leaf count. SPAD values were 44.64 ± 0.84 for *H. illucens*-treated plants (4.7% higher than the control), 43.35 ± 0.59 for NPK-treated plants, and 43.40 ± 0.49 for compost-treated plants, with no significant differences among treatments.

As summarized in Table 2, frass of *H. illucens* increased yield by 62% and NPK by 64% both significantly higher compared to the control ($df = 3$, $F = 4.04$, $p < 0.05$). Total

Table 2 Plant performance following the application of different treatments

Plant performance	Treatment			
	Frass of <i>H. illucens</i>	NPK	Compost	Control
Growth characteristic				
Height (cm)	69.47 ± 3.22^a	71.1 ± 0.79^a	63.95 ± 2.21^{bc}	59.40 ± 2.14^c
Number of leaves	17.85 ± 3.24^a	17.30 ± 1.08^a	16.90 ± 1.72^a	13.45 ± 0.85^a
SPAD	44.64 ± 0.84^a	43.35 ± 0.59^a	43.40 ± 0.49^a	42.66 ± 0.85^a
Yield attribute				
Yield (g/plant)	84.28 ± 12.02^a	85.06 ± 7.37^a	51.32 ± 9.25^b	51.96 ± 8.65^b
Number of filled pods	40.80 ± 4.84^a	43.25 ± 3.44^a	29.00 ± 4.84^b	30.29 ± 4.82^b
Number of empty pods	7.60 ± 2.61^a	6.50 ± 1.82^a	9.05 ± 1.91^a	6.89 ± 2.67^a

Mean $\pm$ standard error. Identical letters following means within the same row indicate no significant differences, as determined by Tukey test at a 5% significance level

pod count showed no significant difference between frass of *H. illucens* and NPK, but both were significantly higher than the control, with increases of 35 and 43%, respectively. Frass of *H. illucens* and NPK treatments enhanced plant growth and productivity, while the number of empty pods remained unaffected across all treatments. The number of empty pods ranged from 6.50 to 9.0 pods/plant across treatments, with no significant differences. Overall, frass of *H. illucens* and NPK treatments improved plant height, yield, and total pod count compared to compost and control treatments.

Effect of different fertilizer types on arthropods

Arthropods abundance

Soil arthropods Table 3 presents a comprehensive overview of soil arthropods identified in the study area, categorized by order, species, and feeding behavior. Among the observed arthropods, ground beetles were the most prevalent. Especially, both *Scarites terricola* and *Dolichus halensis*, predatory species, were present across all treatments, indicating a widespread distribution with no significant treatment effect. In contrast, another predator, *Harpalus variipes*, was commonly found in all treatments except the compost treatment ($df=3$, $\chi^2=16.16$, $p<0.001$). Interestingly, *Anisodactylus tricuspidatus* and *Tachys laetificus*, also predators, were only detected in the frass of *H. illucens* treatment (*A. tricuspidatus*: $df=3$, $\chi^2=2.77$, $p<0.05$; *T. laetificus*: $df=3$,

$\chi^2=24.95$, $p<0.001$). Regarding detritivores, *Armadillidium vulgare* (isopod) was observed in all treatments ($df=3$, $\chi^2=2.40$, $p=0.49$). Meanwhile, the herbivore *Gryllotalpa bimaculatus* from the Orthoptera order was also widespread ($df=3$, $\chi^2=2.77$, $p=0.42$). Finally, the Japanese ant *Tetramorium tsushimae* was present in all treatments except the control group ($df=3$, $\chi^2=10.41$, $p<0.05$).

Figure 1 shows the abundance of different insect groups (predators, detritivores, and herbivores) under the soil amendment treatments (frass of *H. illucens*, NPK, Compost, and Control) in July and August. In July, the predator group under the frass of *H. illucens* treatment had the highest abundance at an average of 4.50 ± 1.32 , followed by the predator group in the NPK treatment with an average 1.50 ± 0.86 ($df=3$, $\chi^2=20.09$, $p<0.001$). In August, the herbivore group in the frass of *H. illucens* treatment had the highest abundance at an average 2.00 ± 1.35 and a predator abundance of 3.30 ± 1.37 ($df=3$, $\chi^2=10.01$, $p<0.05$).

Foliar arthropods This study investigated trophic interactions involving frass of *H. illucens*, NPK, compost, and control treatments, focusing on various species (Table 4). *Condylostylus* sp. and Chironomidae showed differing responses, with *Condylostylus* sp. significantly affected by compost, control, and NPK treatments ($df=3$, $\chi^2=10.96$, $p<0.001$), while Chironomidae showed no significant treatment effect ($df=3$, $\chi^2=3.83$, $p=0.27$). Dipteran species such as *Conicera* sp. and Phoridae had minimal impacts

Table 3 Average number of individuals ($\pm$ standard error) of soil arthropod family/species after the application of different treatments

Order	Family/species	Role	Treatment				Sign
			Frass of <i>H. illucens</i>	NPK	Compost	Control	
Coleoptera	<i>Scarites terricola</i>	PR	0.37 ± 0.18	0.37 ± 0.26	0.00 ± 0.00	0.12 ± 0.12	N.S
	<i>Dolichus halensis</i>	PR	0.37 ± 0.18	0.12 ± 0.12	0.12 ± 0.12	0.12 ± 0.12	N.S
	<i>Agriotes leucephaeatus</i>	HV	0.00 ± 0.00	0.00 ± 0.00	0.12 ± 0.12	0.00 ± 0.00	N.S
	<i>Anisodactylus tricuspidatus</i>	PR	0.12 ± 0.12	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	*
	<i>Tachys laetificus</i>	PR	1.12 ± 0.58	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	***
	<i>Harpalus variipes</i>	PR	1.75 ± 0.86	0.62 ± 0.26	0.37 ± 0.18	0.12 ± 0.12	**
	<i>Holotrichia kiotonensis</i>	HV	0.12 ± 0.12	0.12 ± 0.12	0.00 ± 0.00	0.00 ± 0.00	N.S
	<i>Chlaenius micans</i>	PR	0.00 ± 0.00	0.12 ± 0.12	0.12 ± 0.12	0.12 ± 0.12	N.S
	<i>Harpalus pallidepennis</i>	PR	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.12 ± 0.12	N.S
Isopoda	<i>Philonthus caeruleipennis</i>	PR	0.12 ± 0.12	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	N.S
	<i>Armadillidium vulgare</i>	DV	0.50 ± 0.18	0.37 ± 0.18	0.50 ± 0.37	0.12 ± 0.12	N.S
Orthoptera	<i>Gryllus bimaculatus</i>	HV	0.87 ± 0.74	0.12 ± 0.12	0.12 ± 0.12	0.12 ± 0.12	N.S
	<i>Gryllotalpa orientalis</i>	HV	0.12 ± 0.12	0.00 ± 0.00	0.00 ± 0.00	0.12 ± 0.12	N.S
Hymenoptera	<i>Pristomyrex punctatus</i>	PR	0.00 ± 0.00	0.25 ± 0.16	0.00 ± 0.00	0.12 ± 0.12	N.S
	<i>Tetramorium tsushimae</i>	PR	0.12 ± 0.12	0.12 ± 0.12	0.75 ± 0.61	0.00 ± 0.00	*
Spider	<i>Pardosa astrigera</i>	PR	0.00 ± 0.00	0.12 ± 0.12	0.12 ± 0.12	0.00 ± 0.00	N.S

PR (predator), DV (detritivore), HV (herbivore). Average $\pm$ standard error. Star indicates statistical significance based on GLM analysis with Poisson distribution (*** $p<0.001$, ** $p<0.01$, * $p<0.05$, N.S. $p>0.05$). The same letters after means within the same column are the sign for non-significant difference based on the Tukey test, with a significance level of 5%

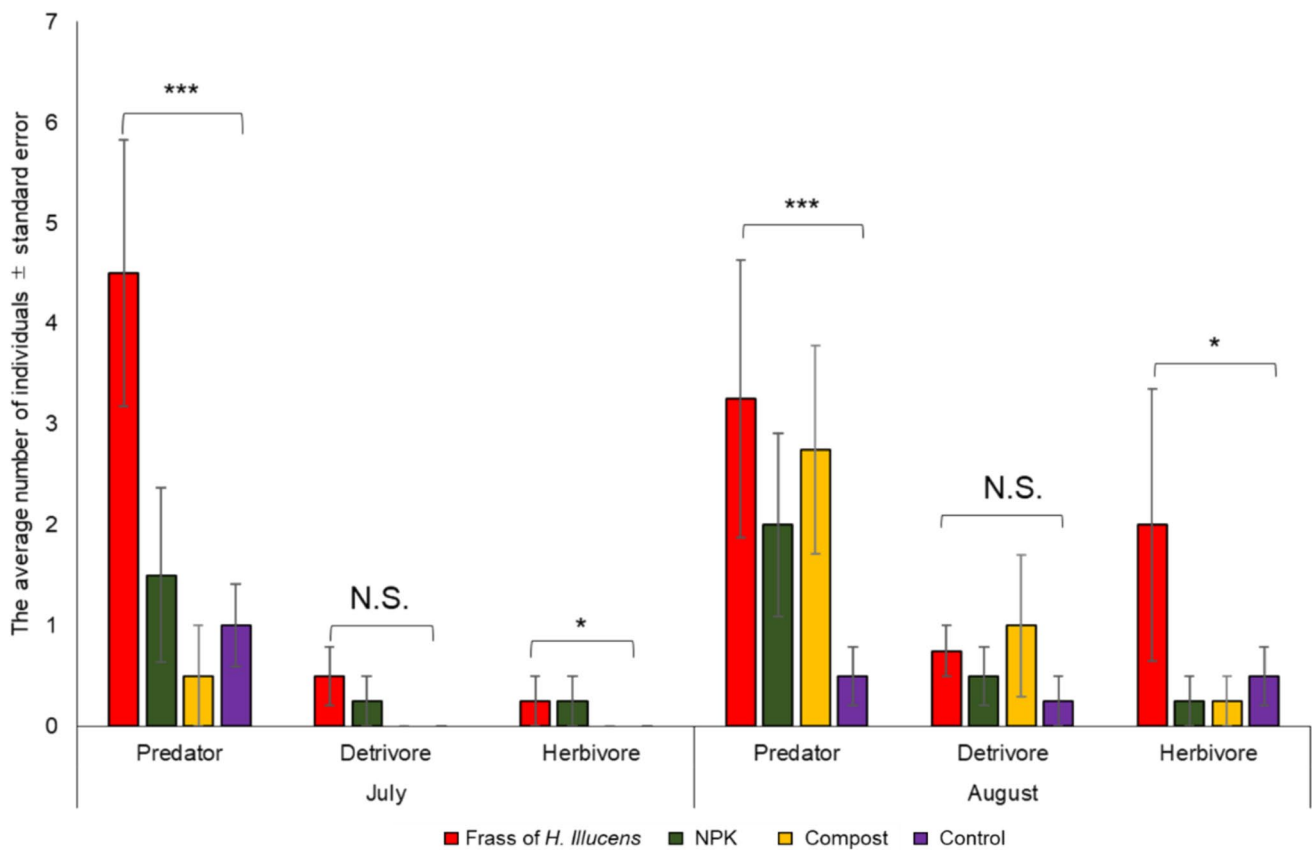


Fig. 1 Soil arthropod species based on trophic composition caught at different treatment plots. Significant differences according to a generalized linear model (GLM), including parameters with Poisson error distribution (***) $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, N.S. $p > 0.05$)

across treatments. *Synopeas* sp. among hymenoptera was significantly influenced by frass of *H. illucens* ($df=3$, $\chi^2=31.90$, $p < 0.001$) and negatively affected by NPK treatments. Thrips (thysanoptera) abundance was significantly higher in compost and control treatments ($df=3$, $\chi^2=20.383$, $p < 0.001$) compared to frass of *H. illucens*, while *Macrosteles* sp. (Hemiptera) showed lower abundance with compost and control treatments ($df=3$, $\chi^2=11.60$, $p < 0.001$) (Fig. 2).

The average number of foliar arthropod individuals across different treatment plots, categorized by trophic composition (predator, scavenger, omnivore, herbivore), demonstrated significant variations influenced by both treatment and month. Predators showed a strong treatment effect ($df=3$, $\chi^2=25.17$, $p < 0.001$) and a significant monthly variation ($df=1$, $\chi^2=25.49$, $p < 0.001$). The application of frass of *H. illucens* resulted in the highest average number of individuals (19.75 ± 3.94 in July and 8.75 ± 4.71 in August), approximately twofold higher compared to other treatments. Scavengers were significantly affected by treatment ($df=3$, $\chi^2=20.829$, $p < 0.001$) but not by month ($df=1$, $\chi^2=0.276$, $p > 0.05$). Herbivores displayed the most pronounced treatment impact ($df=3$, $\chi^2=52.32$, $p < 0.001$) and the highest

sensitivity to monthly changes ($df=1$, $\chi^2=77.50$, $p < 0.001$). Herbivorous arthropods were further classified into two functional subgroups: edamame-associated pests and generalist herbivores. Edamame-associated pests included chewing herbivores, leaf miners, and leafhoppers known to cause direct foliar damage, such as thrips, leafhoppers (*Macrosteles* sp.), and orthopterans. In addition, Japanese beetles (*Popillia japonica*), although not captured by the trapping methods used, were occasionally observed feeding on edamame foliage during field inspections and were, therefore, considered as potential edamame-associated pests. Generalist herbivores comprised species with incidental or non-specific plant-feeding behavior and limited contribution to observable leaf damage. In July, the control and compost had the highest average herbivores, but in August frass of *H. illucens* and NPK had the highest. These results indicate differential responses of trophic groups to treatment types and temporal factors, with predators and herbivores being more responsive to both variables compared to scavengers.

In summary, this study showed that frass of *H. illucens* treatment strongly influences foliar arthropod populations in edamame plants. It increased beneficial predators, maintained a balanced community of other species, and in some

Table 4 Average number of individuals ($\pm$ standard error) of foliar arthropod family/species after the application of different treatments

Order	Family/species	Role	Treatment				Sign
			BSF Frass	NPK	Compost	Control	
Diptera	<i>Condylostylus</i> sp.	PR	0.12 $\pm$ 0.25	1.37 $\pm$ 0.25	1.75 $\pm$ 1.03	1.87 $\pm$ 0.85	***
	<i>Thrypticus smaragdinus</i>	PR	1.25 $\pm$ 2.25	1.37 $\pm$ 1.03	2.37 $\pm$ 1.43	2.75 $\pm$ 2.01	N.S
	<i>Agromyza wistariae</i>	HV	1.50 $\pm$ 1.08	0.37 $\pm$ 0.47	1.62 $\pm$ 2.00	0.87 $\pm$ 1.18	*
	<i>Conicera</i> sp.	SC	0.00 $\pm$ 0.00	0.12 $\pm$ 0.25	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	***
	Sciaridae	SC	0.50 $\pm$ 0.57	0.75 $\pm$ 0.47	1.75 $\pm$ 2.00	3.50 $\pm$ 1.43	*
	Phoridae	SC	0.37 $\pm$ 0.75	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	N.S
	Chironomidae	SC	2.25 $\pm$ 1.31	3.00 $\pm$ 1.00	2.25 $\pm$ 1.01	2.37 $\pm$ 0.96	N.S
	<i>Musca domestica</i>	SC	0.37 $\pm$ 0.26	1.12 $\pm$ 0.58	0.25 $\pm$ 0.25	2.75 $\pm$ 2.75	N.S
	Drosophilidae	HV	0.37 $\pm$ 0.37	0.00 $\pm$ 0.00	0.12 $\pm$ 0.12	0.00 $\pm$ 0.00	N.S
	<i>Sarcophaga peregrina</i>	SC	0.37 $\pm$ 0.26	0.00 $\pm$ 0.00	0.37 $\pm$ 0.18	0.50 $\pm$ 0.18	N.S
	<i>Pteticus tenebrifer</i>	SC	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.12 $\pm$ 0.12	0.12 $\pm$ 0.12	N.S
	Agromyzidae	HR	0.12 $\pm$ 0.12	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	N.S
Hymenoptera	<i>Synopeas</i> sp.	PR	5.50 $\pm$ 1.79	1.25 $\pm$ 0.49	1.62 $\pm$ 0.86	2.00 $\pm$ 0.80	***
	Encyrtidae	PR	1.25 $\pm$ 1.25	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	***
	<i>Cotesia</i> sp.	PR	0.62 $\pm$ 0.37	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	**
	Eulophidae	PR	0.00 $\pm$ 0.00	1.00 $\pm$ 0.53	0.12 $\pm$ 0.12	0.12 $\pm$ 0.12	**
	<i>Pristomyrex punctatus</i>	PR	1.25 $\pm$ 0.81	0.12 $\pm$ 0.12	0.00 $\pm$ 0.00	0.25 $\pm$ 0.25	***
	Tenthredinidae	PR	2.25 $\pm$ 2.11	0.37 $\pm$ 0.37	0.00 $\pm$ 0.00	0.62 $\pm$ 0.62	***
	Braconidae	PR	0.12 $\pm$ 0.12	0.75 $\pm$ 0.36	0.00 $\pm$ 0.00	0.12 $\pm$ 0.12	*
	<i>Anagrus</i> sp.	PR	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.12 $\pm$ 0.12	0.00 $\pm$ 0.00	N.S
	Mymaridae	PR	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.25 $\pm$ 0.25	0.25 $\pm$ 0.25	N.S
	Eurytomidae	PR	1.00 $\pm$ 1.00	0.00 $\pm$ 0.00	0.75 $\pm$ 0.49	1.12 $\pm$ 0.54	**
	<i>Tetramorium tsushimae</i>	PR	0.00 $\pm$ 0.00	0.62 $\pm$ 0.41	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	**
Thysanoptera	Thrips	HV	5.75 $\pm$ 2.81	7.25 $\pm$ 2.82	15.50 $\pm$ 3.97	16.12 $\pm$ 3.20	N.S
Hemiptera	<i>Macrostes</i> sp.	HV	32.00 $\pm$ 9.73	23.75 $\pm$ 8.20	11.5 $\pm$ 5.08	4.25 $\pm$ 1.27	***
	<i>Dactynotus gobonis</i>	HV	0.50 $\pm$ 0.37	1.12 $\pm$ 0.35	0.12 $\pm$ 0.12	0.62 $\pm$ 0.37	N.S
	<i>Corythucha marmorata</i>	HV	0.12 $\pm$ 0.12	0.00 $\pm$ 0.00	0.25 $\pm$ 0.16	0.12 $\pm$ 0.12	N.S
	<i>Drymus marginatus</i>	HV	1.25 $\pm$ 0.61	0.50 $\pm$ 0.50	0.25 $\pm$ 0.25	0.00 $\pm$ 0.00	**
	<i>Geocoris proteus</i>	HV	1.00 $\pm$ 0.65	0.00 $\pm$ 0.00	0.75 $\pm$ 0.75	0.75 $\pm$ 0.75	N.S
Coleoptera	<i>Goniotecna</i> sp.	PR	0.25 $\pm$ 0.2	0.50 $\pm$ 0.50	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	N.S
	<i>Coelphoracoelophora</i> sp.	PR	0.00 $\pm$ 0.00	0.25 $\pm$ 0.25	0.50 $\pm$ 0.50	0.00 $\pm$ 0.00	N.S
	<i>Lebia viridis</i>	PR	0.25 $\pm$ 0.25	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	N.S
	<i>Medythia nigrobilineata</i>	HV	0.12 $\pm$ 0.12	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	N.S
Orthoptera	<i>Euchonocephalis varius</i>	HV	0.12 $\pm$ 0.12	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	N.S
	<i>Oxya japonica</i>	HV	0.12 $\pm$ 0.12	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	N.S
	<i>Tettigonia orientalis</i>	HV	0.12 $\pm$ 0.12	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	N.S
	<i>Gryllus bimaculatus</i>	HV	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.75 $\pm$ 0.61	0.00 $\pm$ 0.00	**
Odonata	<i>Dipteromimus</i> sp.	HV	0.12 $\pm$ 0.12	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	N.S
Spider	<i>Tetragnata pardosa</i>	PR	0.50 $\pm$ 0.50	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.50 $\pm$ 0.50	N.S
	<i>Pardosa astrigera</i>	PR	0.25 $\pm$ 0.25	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	N.S

PR (predator), HV (herbivore), SC (scavenger). Average $\pm$ standard error. Star indicates statistical significance based on GLM analysis with Poisson distribution (*** p < 0.001, ** p < 0.01, * p < 0.05, N.S. p > 0.05). The same letters after means within the same column are the sign for non-significant difference based on the Tukey test, with a significance level of 5%

cases lowered harmful herbivores. Thus, frass of *H. illucens* is recommended for improving arthropod diversity and plant health.

Community structure

Soil arthropods The arthropod community structure was further analyzed using non-metric multidimensional scaling

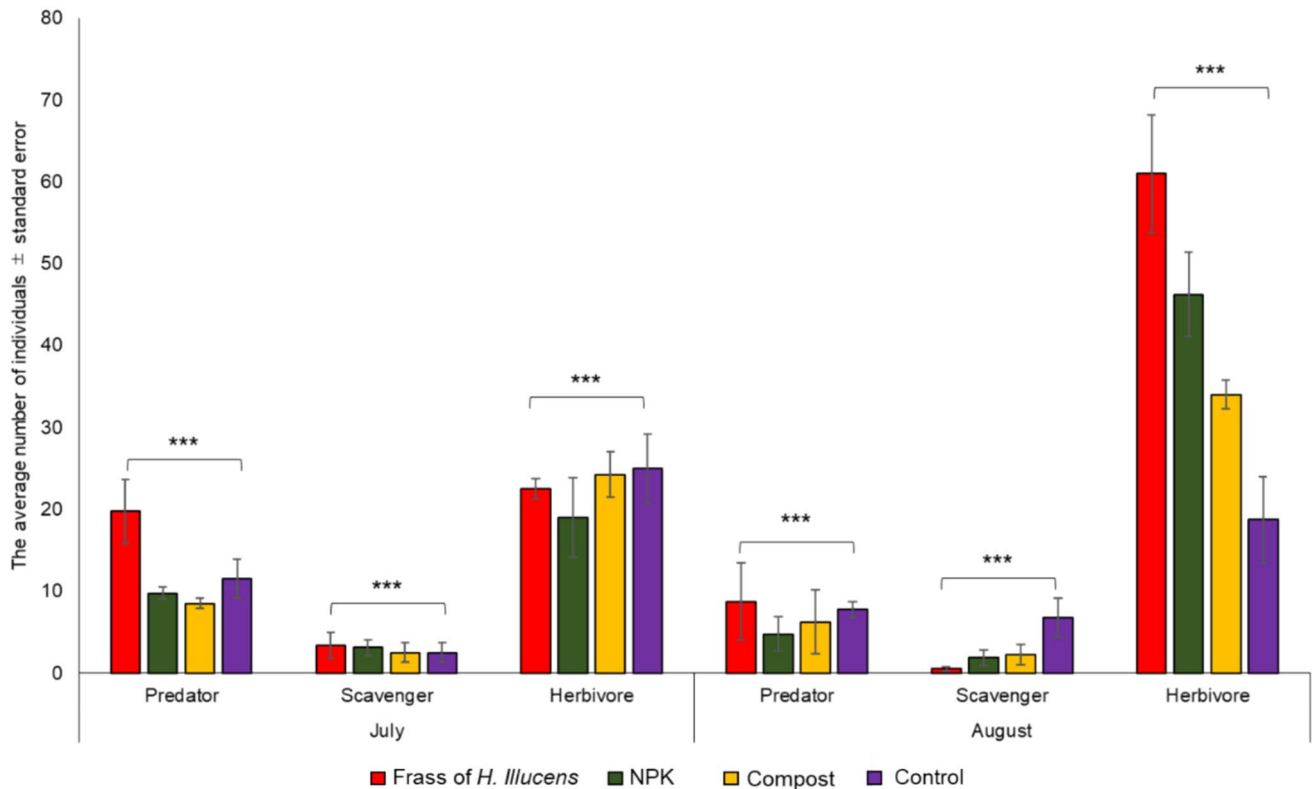


Fig. 2 Foliar arthropod species based on trophic composition caught at different treatment plots. Significant differences according to a generalized linear model (GLM), including parameters with Poisson error distribution (** $p < 0.001$, * $p < 0.01$, $p < 0.05$, N.S. $p > 0.05$)

(NMDS). In Fig. 3, the distance between sampling points was estimated using the Bray–Curtis dissimilarity index and confirmed by analysis of similarity (ANOSIM) on soil

arthropod communities across frass of *H. illucens*, compost, control, and NPK treatments, revealing a statistically significant but small difference in community composition

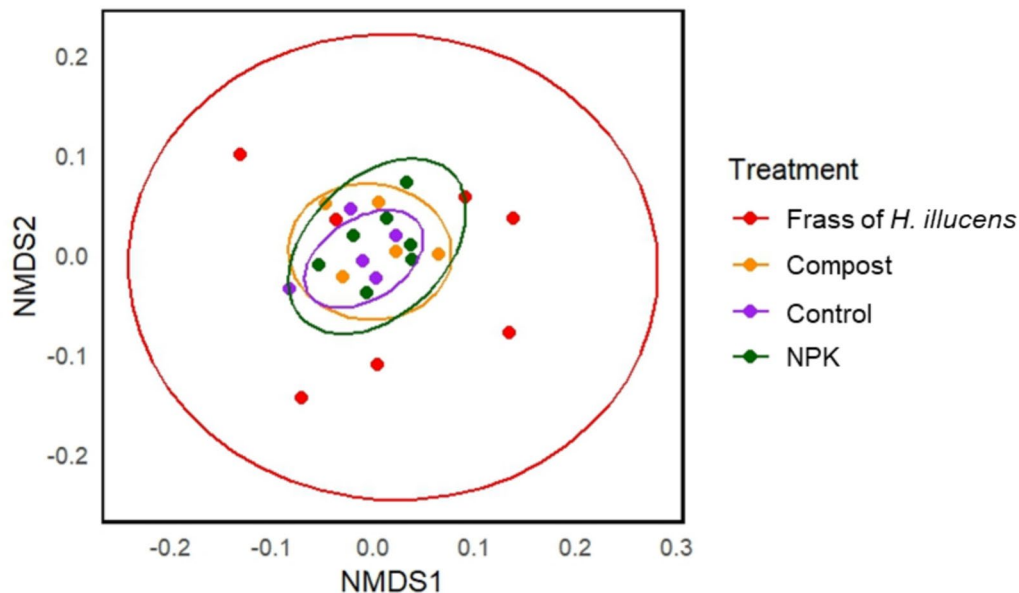


Fig. 3 Non-metric multidimensional scaling (NMDS) ordination of soil arthropod community structure at different treatment plots

($R=0.05$, $p=0.05$). This suggests some non-random variation in arthropod community structure among treatments. The overlapping ellipsoids represent 95% confidence intervals for each treatment, indicating some shared characteristics and distinct differences. The greatest dissimilarity was observed among treatments; frass of *H. illucens* showed the highest dissimilarity, followed by compost, control, and NPK. Hence, different fertilizer treatments affected the soil arthropod community structure, with the application of frass of *H. illucens* having the most distinct impact.

Foliar arthropods The ANOSIM (analysis of similarities) used a dissimilarity matrix based on the Bray–Curtis method to assess differences in community composition among different treatments (Fig. 4). The ANOSIM found a weak separation between groups ($R=0.09$, $p=0.15$). However, the observed differences were not statistically significant.

Plant damage

Leaf damage on edamame plants was visually assessed using a damage scoring system, with representative examples shown in Fig. 5. The observed damage patterns were primarily characterized by chewing holes and partial skeletonization of leaf tissue, which are consistent with injury caused by chewing herbivorous insects rather than piercing–sucking feeders.

The percentage of damaged leaves was monitored over 4 consecutive weeks under four treatments: frass of *H. illucens*, NPK fertilizer, compost, and a control. In the first week, all treatments started with low levels of plant

damage and no significant difference ($df=3$, $p=0.64$) among the treatments. In the second week, there was a significant increase in plant damage for the NPK, compost, and control groups, reaching approximately 15–16%. In contrast, frass of *H. illucens* maintained consistently low damage levels of about 5% ($df=3$, $p=0.02$) (Fig. 6).

In the third and fourth weeks, plant damage continued to rise in the NPK, compost, and control groups. In week 4, NPK showed the highest damage percentage at $20.6 \pm 1.54\%$, followed by compost at $18.7 \pm 4.73\%$, and control at $17.9 \pm 1.84\%$. Frass of *H. illucens*, however, showed only a small increase at $6.5 \pm 1.08\%$ ($df=3$, $p=0.012$). This trend demonstrates that frass of *H. illucens* is highly effective in minimizing plant damage compared to other treatments, while NPK, compost, and control exhibited greater damage over time.

The PCA biplot (Fig. 7) indicates a clear separation of the frass of *H. illucens* treatment from the other treatments, primarily driven by its association with higher predator activity and lower levels of plant damage. This separation is primarily driven by its association with higher predator activity and lower levels of plant damage. In contrast, the compost and NPK treatments cluster closer to the herbivore and plant damage vectors, indicating comparatively greater herbivore pressure. Among these treatments, NPK exhibited the highest plant damage ($20.6 \pm 1.54\%$), whereas the frass of *H. illucens* treatment showed the lowest damage ($6.5 \pm 1.08\%$). The control treatment occupied an intermediate position in the ordination space, reflecting moderate plant damage and a weak association with predator abundance.

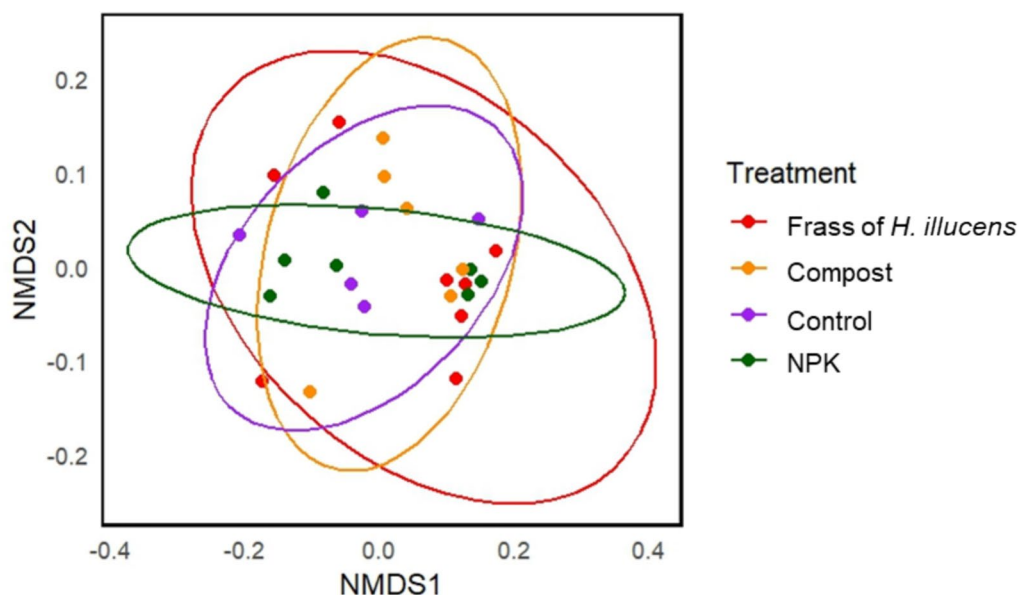


Fig. 4 Non-metric multidimensional scaling (NMDS) ordination of foliar arthropod community structure at different treatment plots



Fig. 5 Representative leaf damage caused by insect pests, illustrating the damage severity scoring scale from 1 (no visible damage) to 5 (severe damage with extensive leaf tissue loss)

Discussion

Fertilizers are fundamental in agriculture, supplying essential nutrients to crops, yet the rising cost of synthetic inputs has emphasized the need for sustainable alternatives (Christel et al. 2021). Black soldier fly (*H. illucens*) frass has demonstrated comparable effectiveness to NPK in improving yield and nutrient efficiency in crops, such as maize and ryegrass (Tanga et al. 2022; Rodgers et al. 2024). Our findings support these results, showing that frass maintained crop productivity while also enhancing arthropod abundance, thereby contributing to ecosystem services. Its effectiveness, however, depends on feedstock composition and nutrient profile, particularly the carbon-to-nitrogen ratio, which influences mineralization and plant growth (Romano et al. 2021; Kawasaki et al. 2020; Nguyen et al. 2020; Chiam et al. 2021). Beyond nutrients, frass contains chitin and microbial residues that stimulate beneficial soil microbes and induce plant defenses (Houben et al. 2020; Setti et al. 2019). Together with its role in recycling organic waste into high-value inputs, this dual function highlights frass as both a fertilizer and a

contributor to sustainable nutrient cycling (Parodi et al. 2018; Gold et al. 2018).

Beyond its agronomic role, frass of *H. illucens* also shaped soil and foliar arthropod communities. NMDS analysis indicated clear shifts in soil arthropod composition, likely driven by enhanced organic matter and microbial activity. Similar frass-mediated increases in springtails, ground beetles, and isopods have been reported, showing its contribution to belowground biodiversity (Viketoft et al. 2021; Brusse et al. 2024). Aboveground, frass plots supported higher arthropod abundance across trophic levels, particularly predators and scavengers, in contrast to compost, which was linked with greater herbivore pressure and plant damage. These patterns align with studies showing that organic inputs stimulate microbial activity and indirectly foster foliar diversity (Watson et al. 2021; Kowaljew et al. 2017). While excessive nitrogen inputs are known to favor herbivores by altering plant tissue quality, predator activity in frass plots appeared to offset this effect, reducing plant damage (Li et al. 2021; Lu et al. 2007).

The responses observed under frass treatments likely reflect both ecological interactions and defense activation.

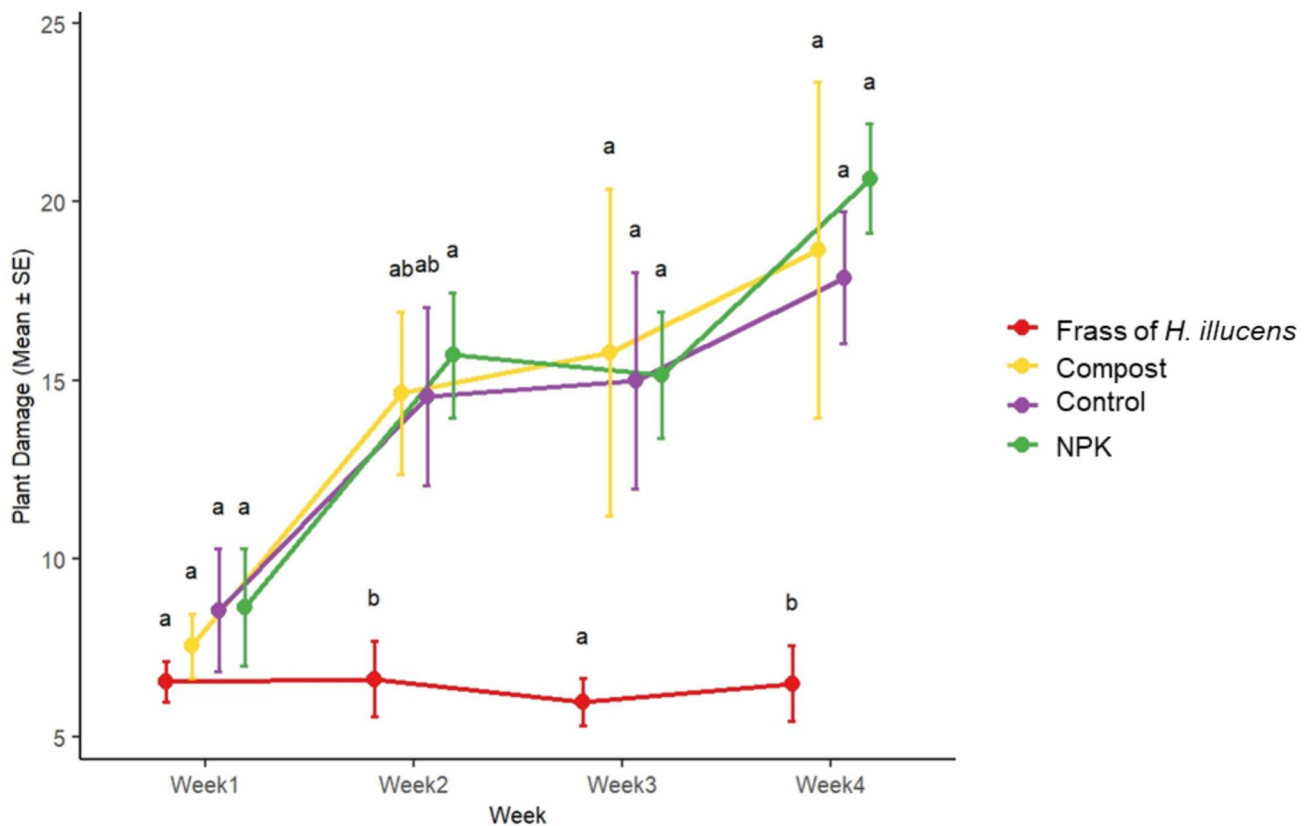


Fig. 6 Mean ($\pm$ SE) number of damaged plants over time in edamame plots in the field after fertilizer application. Means marked with different letters are significantly different, as determined by the Tukey HSD test at a 5% significance level

In edamame, frass application enhanced plant vigor and supported beneficial arthropods, correlating with reduced leaf damage. Similar effects have been noted elsewhere, where frass-derived organic matter, microbes, and chitin fragments triggered *jasmonic acid* (JA) and *salicylic acid* (SA) pathways, priming systemic resistance against herbivores and pathogens (Sharp 2013; Ray et al. 2016; Poveda 2021). For instance, in maize, frass of *H. illucens* fertilizer stimulated defense genes, such as *pr-5*, *mpi*, and *lox-3*, which strengthen pathogen resistance, inhibit insect digestion, and activate JA signaling, thereby reducing feeding damage by *Spodoptera frugiperda* (Mutiyambai et al. 2025). Comparable outcomes have been observed with *Delia radicum* and *Plutella xylostella*, where survival was suppressed in frass-amended systems (Chia et al. 2024). Frass also improves soil fertility through enhanced microbial biomass and enzyme activity (Bruno et al. 2019; Jiang et al. 2019), while its microbial communities may provide antagonistic activity against plant pathogens (Gold et al. 2020; Wynants et al. 2019). These

combined mechanisms—defense priming, soil improvement, and predator activity—likely explain the suppression of herbivory observed in edamame, though outcomes remain context-dependent and influenced by soil conditions, microbial colonization, and application rates (Houben et al. 2020; Van Zan et al. 2024; Wantulla et al. 2024; Schmitt & de Vries 2020; Barragán-Fonseca et al. 2022).

Overall, frass of *H. illucens* emerges as a sustainable alternative to synthetic fertilizers, providing both agronomic and ecological benefits. By improving yields, enhancing soil properties, and fostering diverse arthropod communities, it offers potential for more resilient and environmentally friendly farming systems. With proper feedstock management and application practices, frass could become a cornerstone of sustainable agriculture and integrated pest regulation. Future studies integrating direct plant injury assessments, pest life-stage observations, and long-term field evaluations will be critical for elucidating the mechanisms underlying these effects and for validating the role of frass of *H. illucens* in sustainable fertilization and biologically mediated pest regulation.

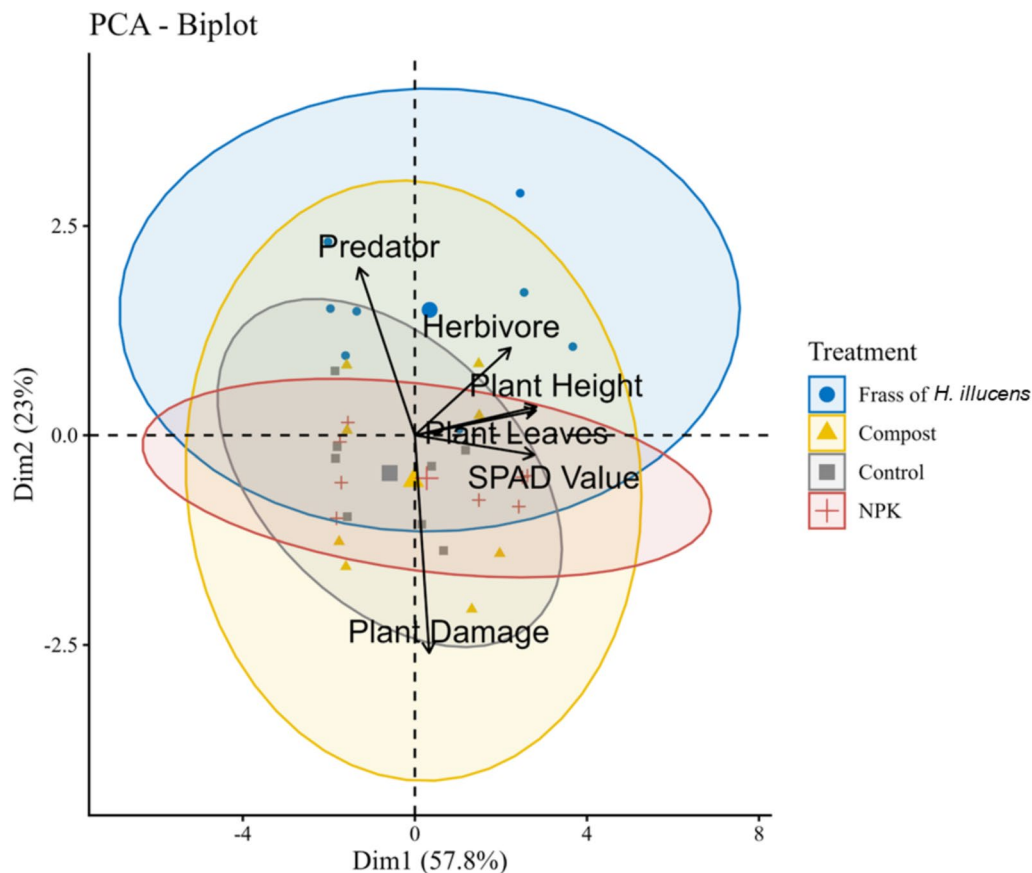


Fig. 7 Principal component analysis (PCA) visualization of plant damage at different treatment plots

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13355-026-00960-0>.

Data availability The datasets generated and analysed during the current study are available from the corresponding author on reasonable request. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Agustiyani D, Agandi R, Arinafril, Nugroho AA, Antonius S (2021) The effect of application of compost and frass from black soldier fly Larvae (*Hermetia illucens* L) on growth of pakchoi (*Brassica rapa* L). IOP Conf Ser: Earth Environ Sci 762(1):012036. <https://doi.org/10.1088/1755-1315/762/1/012036>
- Anedo EO, Beesigamukama D, Mochoge B, Korir NK, Haukeland S, Cheseto X, Nyongesa M, Pwapiwai P, Subramanian S, Tenkouano A, Kibaara B, Tanga CM (2025) Unpacking the benefits of black soldier fly frass fertilizer towards nematode suppression and potato production. Front Plant Sci 16:1509643
- Beesigamukama D, Mochoge B, Korir NK, Fiaboe KKM, Nakimbugwe D, Khamis FM, Subramanian S, Dubois T, Musyoka MW, Ekesi S, Kelemu S, Tanga CM (2020a) Exploring black soldier fly frass as novel fertilizer for improved growth, yield, and nitrogen use efficiency of maize under field conditions. Front Plant Sci 11:574592. <https://doi.org/10.3389/fpls.2020.574592>
- Barragán-Fonseca KY, Nurfikari A, Van De Zande EM, Wantulla M, Van Loon JJA, De Boer W, Dicke M (2022) Insect frass and exuviae to promote plant growth and health. Trends Plant Sci 27:646–654. <https://doi.org/10.1016/j.tplants.2022.04.002>
- Beesigamukama D, Mochoge B, Korir NK, Musyoka MW, Fiaboe KKM, Nakimbugwe D, Khamis FM, Subramanian S, Dubois T, Ekesi S, Tanga CM (2020b) Nitrogen fertilizer equivalence of black soldier fly frass fertilizer and synchrony of nitrogen mineralization for maize production. Agronomy 10(9):1395. <https://doi.org/10.3390/agronomy10091395>
- Borror DJ, Triplehorn CA, Johnson NF (1996) An introduction to the study of insects, 6th edn. Saunders College Publishing, Philadelphia (Indonesian translation by Partosoedjono S, Gadjah Mada University Press, Yogyakarta)
- Borkent S, Hodge S (2021) Glasshouse evaluation of the black soldier fly waste product hexafrass™ as an organic fertilizer. InSects 12(11):977. <https://doi.org/10.3390/insects12110977>

- Bruno D, Bonelli M, De Filippis F, Di Lelio I, Tettamanti G, Casaretti M, Ercolini D, Caccia S (2019) The intestinal microbiota of *Hermetia illucens* larvae is affected by diet and shows a diverse composition in the different midgut regions. *Appl Environ Microbiol* 85:e01864–e1918. <https://doi.org/10.1128/AEM.01864-18>
- Brusse T, Thénard J, Marrec R, Caro G (2024) Assessing the drivers of grassland ground-dwelling arthropod community composition: integrating landscape-scale farming intensity and local environmental conditions. *Sci Total Environ* 930:172754. <https://doi.org/10.1016/j.scitotenv.2024.172754>
- Burks CS, Brandl DG (2005) Quantitative assessment of insect pest damage to figs. *Crop Manag* 4(1):1–7
- Carter MR, Noronha C (2007) Soil micro-arthropod communities and microbial parameters in the potato ridge under two field management systems on sandy loams in Atlantic Canada. *Can J Soil Sci* 87(1):39–49. <https://doi.org/10.4141/CJSS06013>
- Chavez MY, Uchanski M, Tomberlin JK (2024) Impacts of black soldier fly, *Hermetia illucens*, larval frass on lettuce and arugula production. *Front Sustain Food Syst* 8:1399932. <https://doi.org/10.3389/fsufs.2024.1399932>
- Chia S, Van Loon J, Dicke M (2024) Effects of frass from larvae of black soldier fly (*Hermetia illucens*) and yellow mealworm (*Tenebrio molitor*) on growth and insect resistance in field mustard (*Brassica rapa*): differences between insect species and frass treatments. *Entomol Exp Appl* 172:394–408. <https://doi.org/10.1111/eea.13425>
- Chiam Z, Lee JTE, Tan JKN, Song S, Arora S, Tong YW, Tan HTW (2021) Evaluating the potential of okara-derived black soldier fly larval frass as a soil amendment. *J Environ Manage* 286:112163. <https://doi.org/10.1016/j.jenvman.2021.112163>
- Christel A, Maron PA, Ranjard L (2021) Impact of farming systems on soil ecological quality: a meta-analysis. *Environ Chem Lett* 19(6):4603–4625. <https://doi.org/10.1007/s10311-021-01302-y>
- de Van Zan EM, Wantulla M, van Loon JJA, Dicke M (2024) Soil amendment with insect frass and exuviae affects rhizosphere bacterial community, shoot growth and carbon/nitrogen ratio of a brassicaceous plant. *Plant Soil* 495(1–2):631–648. <https://doi.org/10.1007/s11104-023-06351-6>
- Elissen H, van der Weide R, Gollenbeek L (2023) Effects of black soldier fly frass on plant and soil characteristics: a literature overview. Wageningen Plant Research, Wageningen, pp 1–23
- Fischer H, Romano N, Sinha AK (2021) Conversion of spent coffee and donuts by black soldier fly (*Hermetia illucens*) larvae into potential resources for animal and plant farming. *InSects* 12(4):332. <https://doi.org/10.3390/insects12040332>
- Gebremikael MT, van Wickeren N, Hosseini PS, De Neve S (2022) The impacts of black soldier fly frass on nitrogen availability, microbial activities, c sequestration, and plant growth. *Front Sustain Food Syst* 6:795950. <https://doi.org/10.3389/fsufs.2022.795950>
- Gold M, Tomberlin JK, Diener S, Zurbrugg C, Mathys A (2018) Decomposition of biowaste macronutrients, microbes, and chemicals in black soldier fly larval treatment: a review. *Waste Manag* 82:302–318. <https://doi.org/10.1016/j.wasman.2018.10.022>
- Gold M, von Allmen F, Zurbrugg C, Zhang J, Mathys A (2020) Identification of bacteria in two food waste black soldier fly larvae rearing residues. *Front Microbiol* 11:582867. <https://doi.org/10.3389/fmicb.2020.582867>
- Gurung SK, Mickan BS, Middleton JA, Singh PK, Jenkins SN, Rengel Z, Siddique KH, Solaiman ZM (2024) Manure-derived black soldier fly frass enhanced the growth of chilli plants (*Capsicum annuum* L.) and altered rhizosphere bacterial community. *Appl Soil Ecol* 202:105605
- Higley LG, Boethel DJ (eds) (1994) Handbook of soybean insect pests, Vol 1. Entomological Society of America, Lanham
- Houben D, Daoulas G, Faucon MP, Dulaurent AM (2020) Potential use of mealworm frass as a fertilizer: impact on crop growth and soil properties. *Sci Rep* 10(1):61765. <https://doi.org/10.1038/s41598-020-61765-x>
- Jat M, Dohling PNK, Ahuja A, Singh J (2022) Effect of pesticides on soil ecosystem services and processes. *Indian J Entomol* 84(4):981–990. <https://doi.org/10.55446/IJE.2021.5>
- Jiang CL, Jin WZ, Tao XH, Zhang Q, Zhu J, Feng SY, Xu XH, Li HY, Wang ZH, Zhang ZJ (2019) Black soldier fly larvae (*Hermetia illucens*) strengthen the metabolic function of food waste biodegradation by gut microbiome. *Microb Biotechnol* 12:528–543. <https://doi.org/10.1111/1751-7915.13393>
- Kagata H, Ohgushi T (2012) Positive and negative impacts of insect frass quality on soil nitrogen availability and plant growth. *Popul Ecol* 54(1):75–82. <https://doi.org/10.1007/s10144-011-0281-6>
- Kawasaki K, Kawasaki T, Hirayasu H, Matsumoto Y, Fujitani Y (2020) Evaluation of fertilizer value of residues obtained after processing household organic waste with black soldier fly larvae (*Hermetia illucens*). *Sustainability* 12(12):4920. <https://doi.org/10.3390/su12124920>
- Kisaakye J, Beesigamukama D, Haukeland S, Subramanian S, Thiongo PK, Kelemu S, Tanga CM (2024) Chitin-enriched insect frass fertilizer as a biorational alternative for root-knot nematode (*Meloidogyne incognita*) management. *Front Plant Sci* 15:1361739. <https://doi.org/10.3389/fpls.2024.1361739>
- Klammsteiner T, Turan V, Juárez MFD, Oberegger S, Insam H (2020) Suitability of black soldier fly frass as soil amendment and implication for organic waste hygienization. *Agronomy* 10(10):1578. <https://doi.org/10.3390/agronomy10101578>
- Kowaljaw E, Gonzalez-Polo M, Mazzarino MJ (2017) Understanding compost effects on water availability in a degraded sandy soil of Patagonia. *Environ Earth Sci* 76(6):6573. <https://doi.org/10.1007/s12665-017-6573-1>
- Kuo S, Sparks DL (1996) Methods of soil analysis. Chemical methods. Soil Science Society of America Madison, Madison, pp 869–919
- Li Z, Xu B, Du T, Ma Y, Tian X, Wang F, Wang W (2021) Excessive nitrogen fertilization favors the colonization, survival, and development of *Sogatella furcifera* via bottom-up effects. *Plants* 10(5):875. <https://doi.org/10.3390/plants10050875>
- Lomonaco G, Franco A, De Smet J, Scieuzo C, Salvia R, Falabella P (2024) Larval frass of *Hermetia illucens* as organic fertilizer: composition and beneficial effects on different crops. *InSects* 15(4):293. <https://doi.org/10.3390/insects15040293>
- Lu Z, Yu X, Heong K, Hu C (2007) Effect of nitrogen fertilizer on herbivores and its stimulation to major insect pests in rice. *Rice Sci* 14(1):56–66. [https://doi.org/10.1016/S1672-6308\(07\)60009-2](https://doi.org/10.1016/S1672-6308(07)60009-2)
- Mizuno N (1980) The use of H₂SO₄–H₂O₂ for the destruction of plant matter as a preliminary to determination of N, K, Mg, Ca, Fe, Mn. *Jpn J Soil Sci Plant Nutr* 51:418–420
- Mutyambai DM, Mutua JM, Jalloh AA, Beesigamukama D, Kessler A, Subramanian S, Dubois T, Ekese S, Tanga CM (2025) Insect frass fertilizer upregulates maize defence genes and resistance against an invasive herbivore pest. *Sci Rep* 15:29978. <https://doi.org/10.1038/s41598-025-14883-3>
- Nguyen VT, Le TH, Bui XT, Nguyen TN, Lin C, Nguyen HH, Nguyen DD, Senoro DB, Dang BT (2020) Effects of C/N ratios and turning frequencies on the composting process of food waste and dry leaves. *Bioresour Technol Rep* 11:100527. <https://doi.org/10.1016/j.biteb.2020.100527>
- Ning C, Gao P, Wang B, Lin W, Jiang N, Cai K (2017) Impacts of chemical fertilizer reduction and organic amendments supplementation on soil nutrient, enzyme activity, and heavy metal content. *J Integr Agric* 16(8):1819–1831. [https://doi.org/10.1016/S2095-3119\(16\)61476-4](https://doi.org/10.1016/S2095-3119(16)61476-4)
- Parodi A, Leip A, De Boer IJM, Slegers PM, Ziegler F, Temme EH, Herrero M, Tuomisto H, Valin H, Van Middelaar CE, Van Loon

- JJA (2018) The potential of future foods for sustainable and healthy diets. *Nat Sustain* 1:782–789. <https://doi.org/10.1038/s41893-018-0189-7>
- Poveda J (2021) Insect frass in the development of sustainable agriculture: a review. *Agron Sustain Dev* 41:5. <https://doi.org/10.1007/s13593-020-00656-x>
- Ray S, Basu S, Rivera-Vega LJ, Acevedo FE, Louis J, Felton GW, Luthe DS (2016) Lessons from the far end: caterpillar frass-induced defenses in maize, rice, cabbage, and tomato. *J Chem Ecol* 42(11):1130–1141. <https://doi.org/10.1007/s10886-016-0776-x>
- Rehan I, Lopes I, Murta D, Lidon F, Fareleira P, Esteves C, Moreira O, Menino R (2024) Agronomic potential of *Hermetia illucens* frass in the cultivation of ryegrass in distinct soils. *J Insects Food Feed*. <https://doi.org/10.1163/23524588-00001242>
- Rodgers E, Nicolson E, Lauder S, Hodge S (2024) Response of pasture grasses to organic fertilizer produced from black soldier fly frass. *Plants* 13(7):943. <https://doi.org/10.3390/plants13070943>
- Rostami M, Zamani AA, Goldasteh S, Shoushtari RV, Kheradmand K (2012) Influence of nitrogen fertilization on the biology of *Aphis gossypii* (Hemiptera: Aphididae) reared on *Chrysanthemum indicum* (Asteraceae). *J Plant Prot Res* 52(1):118–121. <https://doi.org/10.2478/v10045-012-0019-2>
- Schmitt E, de Vries W (2020) Potential benefits of using *Hermetia illucens* frass as a soil amendment on food production and for environmental impact reduction. *Curr Opin Green Sustain Chem* 25:100325. <https://doi.org/10.1016/j.cogsc.2020.03.005>
- Sharp RG (2013) A review of the applications of chitin and its derivatives in agriculture to modify plant–microbial interactions and improve crop yields. *Agron* 3:757–793. <https://doi.org/10.3390/agronomy3040757>
- Setti L, Francia E, Pulvirenti A, Gigliano S, Zaccardelli M, Pane C, Caradonia F, Bortolini S, Maistrello L, Ronga D (2019) Use of black soldier fly (*Hermetia illucens* (L.), Diptera: Stratiomyidae) larvae processing residue in peat-based growing media. *Waste Manag* 95:278–288. <https://doi.org/10.1016/j.wasman.2019.06.017>
- Song S, Ee AWL, Tan JKN, Cheong JC, Chiam Z, Arora S, Lam WN, Tan HTW (2021) Upcycling food waste using black soldier fly larvae: effects of further composting on frass quality, fertilizing effect, and its global warming potential. *J Clean Prod* 288:125664. <https://doi.org/10.1016/j.jclepro.2020.125664>
- Tanga CM, Beesigamukama D, Kassie M, Egonu PJ, Ghemoh CJ, Nkoba K, Subramanian S, Anyega AO, Ekesi S (2022) Performance of black soldier fly frass fertilizer on maize (*Zea mays* L.) growth, yield, nutritional quality, and economic returns. *J Insects Food Feed* 8(2):185–196. <https://doi.org/10.3920/JIFF2021.0012>
- Teuben A, Roelofsma T (1990) Dynamic interactions between functional groups of soil arthropods and microorganisms during decomposition of coniferous litter in microcosm experiments. *Biol Fertil Soils* 9:145–151. <https://doi.org/10.1007/BF00335798>
- Viketoft M, Riggi LGA, Bommarco R, Hallin S, Taylor AR (2021) Type of organic fertilizer rather than organic amendment per se increases abundance of soil biota. *PeerJ* 9:e11204. <https://doi.org/10.7717/peerj.11204>
- Virla EG, Albarracín EBL, Díaz C, Van Nieuwenhove GA, Fernández FD, Araújo MVC, Melchert NA, Conci LR, Pecci MPG (2023) Bottom-up effect of nitrogen fertilization on the density of the corn leafhopper and its impact on both disease incidence and natural parasitism. *J Pest Sci* 96(1):93–104. <https://doi.org/10.1007/s10340-022-01500-9>
- Wang M, Xu Y, Ni H, Ren S, Li N, Wu Y, Yang Y, Liu Y, Liu Z, Liu Y, Shi J, Zhang Y, Jiang L, Tu Q (2023) Effect of fertilization combination on cucumber quality and soil microbial community. *Front Microbiol* 14:1122278. <https://doi.org/10.3389/fmicb.2023.1122278>
- Wantulla M, Dicke M, van Loon JJA (2024) Effects of amending soil with black soldier fly frass on survival and growth of the cabbage root fly (*Delia radicum*) depend on soil type. *J Pest Sci* 97(3):1451–1459. <https://doi.org/10.1007/s10340-023-01710-9>
- Watson C, Schlösser C, Vögel J, Wichern F (2021) Excellent excrement? Frass impacts on a soil's microbial community, processes, and metal bioavailability. *Appl Soil Ecol* 168:104110. <https://doi.org/10.1016/j.apsoil.2021.104110>
- Wynants E, Frooninckx L, Crauwels S, Verreth C, De Smet J, Sandrock C, Wohlfahrt J, Van Schelt J, Depraetere S, Lievens B, Van Miert S, Claes J, Van Campenhout L (2019) Assessing the microbiota of black soldier fly larvae (*Hermetia illucens*) reared on organic waste streams on four different locations at laboratory and large scale. *Microb Ecol* 77:913–930. <https://doi.org/10.1007/s00248-018-1286-x>
- Yudistira DH, Sandi YU, Wirabumi BA, Damayanti A, Wikandari P, Sato S (2025) Effects of different application doses of black soldier fly frass *Hermetia illucens* (Diptera: Stratiomyidae) on soybean plant performances and arthropod abundance. *Asian J Agric* 9(1):40–51. <https://doi.org/10.13057/asianjagric/g090105>

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