Published by
NIGERIAN SOCIETY OF PHYSICAL SCIENCES
Available online @ https://asr.nsps.org.ng/index.php/asr

African Scientific Reports 5 (2026) 568

African Scientific Reports

Comparative efficacy of insect-based fertilizers: physicochemical properties and their implications for the growth of *Brassica rapa* subsp. chinensis

Ikram Ullah[a], Hadura Abu Hasan[a,b,*]

[a]*School of Biological Sciences, Universiti Sains Malaysia, 11800 Penang, Malaysia*
[b]*Vector Control Research Unit, Universiti Sains Malaysia, 11800 Penang, Malaysia*

Abstract

Insect frass offers a sustainable alternative to chemical fertilisers for optimal crop growth. This study evaluated the efficacy of frass from three edible insects, namely *Hermetia illucens* (black soldier fly), *Teleogryllus commodus* (black field cricket), and *Tenebrio molitor* (mealworm), on the growth of *Brassica rapa* subsp. chinensis, using a feed substrate, broiler small intestine meal (BSIM). A control group of chemical fertilisers was included for comparison in a controlled environment. The physicochemical qualities exhibited substantial variation among the types of frass, reflecting changes in their nutritional composition and fertilisation quality, while chemical fertiliser showed distinct physicochemical properties compared to the frass. Despite the high nutrient profile of *T. commodus*, *H. illucens* frass produced the greatest plant growth outcomes. Plants treated with *H. illucens* frass recorded the highest values for leaf count (10.8 ± 1.3), leaf length (78.12 ± 2.80 mm), leaf width (43.01 ± 1.31 mm), plant height (153.12 ± 4.24 mm), and stem diameter (13.53 ± 0.43 mm). Furthermore, *H. illucens* promoted the greatest root width (28.55 ± 2.39 mm) and longest root length (48.06 ± 1.00 mm). These results point to the potential of *H. illucens* as a useful biofertilizer for promoting the growth of *Brassica rapa* subsp. chinensis.

DOI: 10.46481/asr.2026.5.3.568

Keywords: Insect frass, *Hermetia illucens*, *Teleogryllus commodus*, *Tenebrio molitor*, *Brassica rapa* subsp. chinensis

Article History:
Received: 06 June 2026
Received in revised form: 21 August 2026
Accepted for publication: 01 October 2026
Available online: 11 November 2026

© 2026 The Author(s). Published by the Nigerian Society of Physical Sciences under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

1. Introduction

In recent years, *Brassica rapa* subsp. chinensis has received considerable attention due to the presence of phytochemicals and antioxidant capacity that add nutraceutical value to it. It contains bioactive compounds that enhance nutritional value, including both antioxidant and non-antioxidant compounds [1]. Moreover, its rapid growth, high yield potential, and adaptability to diverse environmental conditions have made it an important crop for horticultural research and sustainable vegetable production [2]. Nitrogen is one of the most important components for the development and growth of plants, especially leafy vegetables, which require high levels of nitrogen for biomass production and photosynthesis [3]. An imbalance of nitrogen compounds can lead to detrimental effects on the cultivation of leafy vegetables. For example, an excess of ammonium (NH_4^+) can cause leaf damage, stunted growth, increased

*Corresponding Author Tel. No.: +604-653-3515.
Email address: hadura@usm.my (Hadura Abu Hasan)

physiological stress and reduce the availability of one of the important nutrients such as potassium ion (K+), while ammonia (NH3) can make the soil more alkaline and adversely affect plant health [4].

However, sustainable growth requires suitable fertiliser, as chemical fertiliser has numerous negative effects both on the environment and on human health [5]. While organic fertilisers positively impact plant development by enhancing the quality of soil and nutrient availability, leading to healthy growth even with minimal nutrient densities [6], their contaminant profile depends on the composition of the rearing substrate and processing conditions [7], which reduce human exposure to such chemicals [8]. From an environmental perspective, organic fertilisers help to reduce greenhouse gas emissions and to mitigate soil erosion [9]. In contrast, chemical fertilisers leach out quickly, which makes it easier to contaminate water and soil [10]. Thus, there is a need for a sustainable solution that can potentially enhance the quality of crops, such as insect-based fertilisers [11, 12]. These fertilisers have shown importance within the context of the circular bioeconomy, offering a minimal water footprint compared to ruminant-derived organic fertilisers [13], and have been shown to improve plant growth efficiently [14].

Frass, or insect-derived fertilisers, has emerged as a sustainable by-product of insect production systems with considerable potential to improve crop growth and soil fertility. Its chemical composition typically contains elevated levels of essential macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), often surpassing those found in commonly applied organic manures, including poultry manure [15]. Additionally, frass production is associated with a lower water footprint compared to ruminant-derived organic fertilisers, highlighting its role as an environmentally sustainable alternative within modern nutrient management practices [13].

Hermetia illucens frass from an integrated waste disposal site has been shown to improve the biochemical properties of the soil and the development and harvest of *B. rapa* subsp. chinensis when treated as a soil ameliorant [5]. In the same way, in Malaysia, the farming of crickets for mass production aims to produce biomass for aquafeed while generating an unprocessed resource made up of dead common house cricket (CHC) individuals, cuticular wastes, and byproducts that may have fertilising qualities [16]. Additionally, the introduction of *T. molitor* is a possible source of organic fertiliser and has great potential to be used as a partial or a complete substitute for mineral NPK fertiliser [17]. Despite the substantial increase in the use of frass as an organic fertiliser, comparative studies investigating frass from different insect species while reared on the same substrate remain unexplored. In particular, the fertiliser potential of frass produced by *T. commodus*, *H. illucens*, and *T. molitor* reared on broiler small intestine meal (BSIM) has not been systematically compared.

The utilisation of this waste-derived substrate chains the principles of the circular bioeconomy by converting organic waste into value-added fertiliser resources. Thus, this study aims to evaluate the effectiveness of frass derived from *T. molitor*, *T. commodus* and *H. illucens* as fertilisers for *Brassica rapa* subsp. chinensis, compared with chemical fertiliser and a control without fertilisers, to identify their potential role in sustainable agriculture.

2. Materials and methods

2.1. Frass preparation

The frass used in the current study was obtained from three insect species: *Teleogryllus commodus*, *Hermetia illucens*, and *Tenebrio molitor*, which were reared in the insectarium at the School of Biological Sciences, Universiti Sains Malaysia, using a feeding substrate of broiler small intestine meal (BSIM). This sustainable feed is obtained from the poultry slaughterhouse, aligning with the principles of circular bioeconomy. The BSIM, obtained as waste from the broiler slaughtering process, was sourced from the local wet market through Maag Faimal Enterprise (5°19′33.6″N 100°17′12.4″E). The nutritional and mineral analysis of the BSIM was conducted at the School of Chemical Sciences, Universiti Sains Malaysia, as described in Table 1. BSIM fine-textured powder was prepared in Animal and Fish House (5°21′29.1″N 100°17′37.2″E), first by cutting the broilers' small intestines using poultry knives and internal intestinal lining cleaning using portable rapid rotating washing machine, further water-heated with deionized water as medium (20 minutes, 70°C) using an induction cooker (Philips model HD4902/60) for primary microbial sterilization, and microwave oven-dried (30 minutes, 70°C), for drying and secondary microbial sterilization. Dried BSIM were further ground with a high-speed stainless-steel grinder for two minutes till turned into fine-textured powder. BSIM fine-textured powder was subjected to 50% hydration of the current total BSI mass (g) with deionized water. The feed composition is given in Table 1. The BSIM powder was hydrated by adding deionized water equivalent to 50% (w/w) of the dry BSIM mass.

The feed was dried in an oven (Memmert GmbH model ULM 500) at 70°C for 1 h (Figure 1) to prepare powdered Broiler Small Intestine Meal (BSIM), which was subsequently hydrated to 50% moisture content (Figure 2).

Among the three insects, due to the active nature of *T. commodus* nymphs, they were kept in a large container to prevent them from escaping. Frass was operationally defined as the material collected after separating it from the remaining unconsumed feed by sieving. The collected material was first passed through 16 mm and 22 mm sieves to remove large materials, including unconsumed feed, exuviae, insect fragments, and other visible non-frass materials. The separated material was then passed through 2 mm and 3 mm sieves to obtain the frass fraction. The frass was oven-dried at 60°C for 1 h as shown in Figure 3 and subsequently homogenised using a laboratory blender and then placed in a separate container.

Table 1: The nutritional and mineral values of the BSIM. Values are presented as mean ± standard deviation (SD) of three analytical replicates (n = 3).

Parameters	Values
CP	63.52 ± 0.004 %w/w
P	7036.34 ± 2.24 mg kg-1
K	59.05 ± 0.002 mg kg-1
Ca	1123.70 ± 2.20 mg kg-1
Mg	139.59 ± 0.002 mg kg-1
NH_4^+	7307.55 ± 2.20 mg kg-1



Figure 1: Oven drying of broiler's small intestines.

Table 2: The chemical analysis of the soil using the standard analytical methods.

Parameter	Mean
pH	6.39 ± 0.06
Fine and sand [%]	38.90 ± 0.10
Coarse sand [%]	26.90 ± 0.57
Silt [%]	6.10 ± 0.10
Clay [%]	28.10 ± 0.19
Total nitrogen % [% w/w]	0.07 ± 0.00
Organic nitrogen [mg/kg]	1,656.79 ± 9.36
Exchangeable Ammonium NH_4^+ [mg/kg]	9.04 ± 0.09
Exchangeable Nitrite NO2- [mg/kg]	0.01 ± 0.00
Exchangeable Nitrate NO3- [mg/kg]	0.03 ± 0.01
Total Potassium (K) [mg/kg]	21.41 ± 0.03
Exchangeable Potassium (K+) [mg/kg]	15.43 ± 0.04
Electrical Conductivity [μS/cm]	72.75 ± 0.08
C/N Ratio	5.62 ± 0.05
Total Organic Matter (TOM) [% w/w]	8.96 ± 0.02

2.2. Chemical fertiliser

Trio Baja Leaves & Ferns are commonly used fertilisers in this study, mostly used for increasing plant development, especially for leafy plants, ferns, and palms, which have an NPK ratio of 15:15:15.



Figure 2: Ground and fine-powdered Broiler's Small Intestine Meal (BSIM).



Figure 3: Frass drying process for residual moisture removal.

2.3. Determination methods

2.4. Nitrogen and its compounds

Total nitrogen and ammonia were determined using the Kjeldahl method. For nitrogen digestion, 2 g of sample was transferred into a Kjeldahl digestion flask and treated with concentrated sulfuric acid (H_2SO_4) and a suitable Kjeldahl catalyst mixture. The samples were digested at approximately 420°C until a clear digest was obtained and then cooled. The digest was diluted with distilled water and transferred to a 250 mL volumetric flask. A reagent blank was prepared and processed using the same procedure without the sample, and the blank titre was subtracted from the sample titre. Distillation of the sample was carried out after alkalisation with sodium hydroxide (NaOH), and the liberated ammonia was collected in the receiving solution; this was followed by titration using

0.02 N H_2SO_4 until the endpoint indicated by the appropriate indicator was reached. Nitrogen concentration was calculated from the corrected acid titre (sample titre minus blank titre), acid normality, sample mass, and dilution factor. Analytical quality was assessed using replicate determinations and appropriate quality-control procedures. Ammonium (NH_4^+) was determined according to the USP 36 method. Nitrate (NO_3^-) levels were assessed using the colourimetric method described by Ref. [18].

2.5. Phosphorus (P) and potassium (K)

Ultraviolet-visible (UV–Vis) spectroscopy was used for phosphorus determination using the technique of complexing the digestate with a solution comprising sulphuric acid, ammonium molybdate, antimony potassium tartrate, and ascorbic acid [19], while total potassium was determined using flame photometry [18].

2.6. pH and conductivity

pH and conductivity were determined using an aqueous medium of a 1:10 (weight/volume) sample-to-distilled-water ratio. The samples were then shaken for 30 min at 180 revolutions min^{-1} using an orbital and linear shaker. The pH and conductivity were measured using separate meters, one for the conductivity and for the pH [18].

2.7. Moisture

The oven-drying method was used to assess the moisture content. To obtain a constant weight, the samples were dried for 24 hours at 105°C in a hot air oven. The final weight of the dried samples was recorded after cooling it in a desiccator [20]. The dry-weight basis (mg/kg dry matter) was used to express all chemical and nutritional concentrations reported in the present study. Moisture content was calculated using Eq. (1).

$$\text{Moisture content } (\%) = \frac{\text{initial weight} - \text{dry weight}}{\text{initial weight}} \times 100. \tag{1}$$

2.8. Experimental design

Seedlings were grown in cell trays (72 Cell Tray) under controlled conditions at the School of Biological Sciences, Universiti Sains Malaysia, while monitoring sprouting and early development. Frass and chemical fertiliser were applied at the transplanting stage in the pot culture system. All treatments had the same amount of fertiliser applied, which was based on an equivalent nitrogen (N) application rate of 120 kg N/ha instead of equal fertiliser mass. This made sure that all treatments had the same amount of nitrogen. As per the guidelines of the Malaysian Agricultural Research and Development Institute (MARDI), *Brassica rapa* subsp. chinensis needs a specific fertiliser application rate of 60 kg N/ha. In this study, a pot culture system was utilised to assess growth parameters in *B. rapa*. The pot culture system restricts nitrogen availability, as it lacks supplemental nitrogen from subsoil layers, possibly affecting nutrient dynamics and plant growth [21]. Thus, the nitrogen application rate was doubled from the MARDI (Malaysian Agricultural Research and Development Institute) standard of 60 kg N/ha to 120 kg N/ha.

Therefore, doubling the recommended nitrogen rate was intended to minimise nutrient limitation and ensure sufficient nitrogen availability throughout the experimental period. A standard polybag was used for each experimental unit, and 2.5 kg of dry soil was added to each polybag and carefully organised to ensure uniform distribution of the insect frass and chemical fertiliser, following the multi-step (serial) soil dilution method. Deionised water (150 mL per pot) was applied twice daily throughout the experimental period to maintain adequate soil moisture using veterinary-grade stainless-steel syringes (80 mL maximum fluid holding volume; 10 mm diameter stainless-steel hypodermic needle). Drainage holes were included in every polybag to allow extra water to drain freely and avoid waterlogging. A total of 25 polybags, each containing one plant, were used, with five replicates per treatment across five treatments (three insect frass types, one chemical fertilizer, and one unfertilized control). The pots were systematically distributed in rows around the experimental zone and rotated weekly to mitigate possible location influences.

No blocking design was used, and each pot was treated as an independent experimental unit. Every pot was handled as an independent experimental unit. Based on the measured nitrogen concentrations of the frass and chemical fertilizer, the equivalent application rates per polybag (2.5 kg soil) were calculated as 5.57 g for BSF frass, 5.49 g for mealworm frass, 1.65 g for cricket frass, and 10.25 g for the chemical fertilizer. Premixed mixtures were carefully prepared to ensure uniform fertilizer distribution, following the serial soil dilution method. Frass samples from each insect species were prepared in three independent replicates. Following collection, the frass was oven-dried at 60°C for 1 h and subsequently stored under refrigerated conditions until further use and analysis.

2.9. Crop establishment and agronomic practices

The frass samples from *H. illucens*, *T. commodus*, and *T. molitor* were similarly filtered to remove any remaining insect materials from the mature frass. A conventional N:P fertiliser was used as a positive control and labelled as chemical fertiliser. The soil was placed in an oven at 60°C for 30 minutes to reduce the risk of soil-borne pathogens.

2.10. Soil quality assessment

Measuring nitrogen compounds, including total nitrogen, organic nitrogen, and exchangeable ammonium, nitrate, and nitrite, is crucial for assessing the soil nutrient availability for plant growth. Soils are the most important land-based ecosystems, storing approximately two-thirds of terrestrial soil organic carbon [22]. Additionally, potassium levels, the carbon-to-nitrogen (C/N) ratio, and total organic matter (TOM), as well as parameters such as pH, soil texture (fine sand, silt, and clay), and electrical conductivity, as shown in Table 2, provide an understanding of soil acidity, fertility, and salinity. These analyses guide effective soil management practices and improve agricultural productivity by ensuring a proper balance of nutrients and soil conditions for optimal plant growth [23]. The chemical analysis of the soil using standard analytical methods is presented in Table 2. All listed proximate chemical analyses for soils were run by a certified and accredited laboratory in Malaysia, using analytical methods based on AOAC standards (Latimer 2016).

2.11. Data collection and post-harvest analysis

A standard 600 mm digital calliper with ± 0.01 resolution was used to measure the heights [mm], leaf lengths [mm], leaf widths [mm], stem diameters [mm], and shoot diameters [mm] of the shoot system growth. Heights [mm] were measured from the lowest visible stem near the soil surface to the tallest shoot at an interval of weeks starting from the 7th to the 56th day, at seven-day intervals on days 7, 14, 21, 28, 35, 42, 49, and 56 of the experimental periods. Five of the earliest leaves on each seedling in each polybag were identified and selected. Leaf lengths and widths were measured consistently every seven days and averaged to determine the final growth measures, as shown in Figure 5. The measurements of fresh and dry total weights [g], fresh and dry stem weights [g], and fresh and dry shoot weights [g] were recorded. Each part of the harvested *B. rapa* subsp. chinensis seedlings was then dried in a convection air-drying oven at 70°C for 48 hours, and the corresponding dry weights [g] were weighed. For every polybag (replicate) of *Brassica rapa* subsp. chinensis seedlings, data were gathered for each type of frass and chemical fertiliser.

2.12. Statistical analysis

The effects of different fertiliser treatments on plant growth parameters were analysed using one-way analysis of variance (ANOVA) and linear mixed-effects models for repeated measurements, with the unit and treatment time defined as random and fixed effects. Before conducting ANOVA, the assumptions of normality and homogeneity of variance were assessed using the Shapiro–Wilk test and Levene's test, respectively. To account for potential heterogeneity of variances, a bootstrapping procedure was applied. The bootstrapping procedure was incorporated into the inferential analysis to provide robust estimates of the sampling distribution and statistical significance. Pairwise comparisons among treatments were performed using Tukey's significant difference (HSD) post-hoc test, with 1,000 pot-level bootstrap resamples used to estimate the sampling distribution of treatment differences and 95% percentile confidence intervals used to assess the robustness of pairwise treatment differences. All statistical analyses were conducted using IBM SPSS Statistics (version 26.0, 64-bit edition). Data are presented as mean ± standard deviation (SD), and statistical significance was set at $p < 0.05$.

3. Results

The current study was carried out on the frass of three insect species with a positive control chemical fertiliser on the growth of *B. rapa* subsp. chinensis and an unfertilised control. Poveda [7] stated that insect-based fertiliser can potentially replace chemical fertiliser by enhancing the quality of the soil and development of the shoot system by applying nitrogen and other essential nutrients. *Brassica rapa* subsp. chinensis treated with *T. commodus* frass showed reduced growth in the shoot system and fresh and dry biomass, compared to the other treatments and chemical fertiliser. However, *H. illucens* and *T. molitor* frass significantly improved the growth and biomass of *Brassica rapa* subsp. chinensis compared with the other treated frass. The frass chemical analysis is shown in Table 3.

3.1. Plant height measurement

Plant height differed significantly among treatments (Table 4). The tallest plants were detected in the *H. illucens* frass treatment (153.12 ± 4.24 mm), followed by *T. molitor* (141.66 ± 4.59 mm). *T. commodus* frass resulted in shorter plants (118.42 ± 1.78 mm), whereas chemical fertilizer treatment produced an intermediate height (133.08 ± 8.66 mm). The unfertilized control recorded the lowest plant height (67.33 ± 5.88 mm), indicating poor growth performance in the absence of nutrient amendments.

3.2. Leaf measurements

Leaf-related growth parameters of *Brassica rapa* subsp. chinensis varied significantly among treatments (Table 4). Plants treated with *Hermetia illucens* frass produced the highest number of leaves (10.80 ± 1.30), as well as the greatest leaf length (78.12 ± 2.80 mm) and leaf width (43.01 ± 1.31 mm), though not significantly different from *T. molitor* for these two parameters. *Tenebrio molitor* frass also enhanced leaf development, resulting in 8.80 ± 0.84 leaves, a leaf length of 57.26 ± 5.46 mm, and a leaf width of 38.76 ± 1.49 mm, though these values were significantly lower than those observed for *H. illucens*.



Figure 4: Day 1 of *B. rapa* subsp. chinensis after transplanting, showing initial establishment across treatments



Figure 5: Growth progression of *B. rapa* subsp. chinensis at Week 1 after transplanting, showing early establishment across treatments

In contrast, plants receiving *Teleogryllus commodus* frass exhibited reduced leaf growth, with fewer leaves (5.60 ± 1.14), shorter leaf length (33.48 ± 5.48 mm), and narrower leaf width (21.56 ± 2.33 mm). The chemical fertilizer treatment showed intermediate performance, producing 7.40 ± 0.89 leaves, a leaf length of 51.64 ± 3.39 mm, and a leaf width of 36.53 ± 1.56 mm. The unfertilized control recorded the lowest values across all leaf parameters, as shown in Table 4.



Figure 6: Growth progression of *B. rapa* subsp. chinensis at Week 2 after transplanting, highlighting initial vegetative growth



Figure 7: Growth progression of *B. rapa* subsp. chinensis at Week 4 after transplanting, showing advanced vegetative development across treatments

3.3. Stem and root measurements of Brassica rapa

Stem diameter varied significantly across treatments (Table 4). The greatest stem diameter was observed in plants treated with *H. illucens* frass (13.53 ± 0.43 mm), followed by *T. molitor* (12.34 ± 0.24 mm). Plants receiving *T. commodus* frass exhibited a reduced



Figure 8: Growth progression of *B. rapa* subsp. chinensis in the final week after transplanting, representing the pre-harvest growth stage under different treatments

Table 3: The analysis of the physicochemical characteristics of insect-based frass and chemical fertilisers

Parameters	*Hermetia illucens*	*Tenebrio molitor*	*Teleogryllus commodus*	Chemical fertilisers
pH	$8.99 \pm 0.03_{a}$	$8.33 \pm 0.02_{b}$	$6.72 \pm 0.08_{c}$	$5.90 \pm 1.21_{d}$
Moisture [%]	$5.17 \pm 0.25_{a}$	$5.31 \pm 0.25_{a}$	$5.54 \pm 0.52_{ab}$	$5.28 \pm 2.02_{b}$
Conductivity [μS/cm]	$595.67 \pm 5.86_{a}$	$1028.33 \pm 6.51_{b}$	$1131.67 \pm 8.33_{b}$	$987.24 \pm 6.45_{b}$
N [g/kg]	$27.6 \pm 0.53_{a}$	$28 \pm 0.82_{a}$	$93.1 \pm 3.43_{b}$	$150 \pm 0_{b}$
P [g/kg]	$6.50\pm 59.34_{a}$	$6.87 \pm 111.7_{b}$	$7.88 \pm 16.78_{a}$	$150 \pm 0_{b}$
K [g/kg]	$20.56 \pm 72.91_{a}$	$10.48 \pm 13.58_{b}$	$10.27 \pm 65.07_{b}$	$150 \pm 0_{c}$
NH_4^+ [g/kg]	$4.03\pm 1.73_{a}$	$4.76 \pm 3.30_{b}$	$10.30 \pm 2.37_{c}$	$2.47\pm 1.33_{d}$
NO3- [g/kg]	$0.02\pm 1.26_{a}$	$0.02 \pm 5.43_{a}$	$0.13\pm 7.20_{b}$	$0.04 \pm 1.34_{a}$
TOM % w/w	$74.70 \pm 5.77_{a}$	$66.54 \pm 5.42_{b}$	$86.50 \pm 1.42_{c}$	$41.20 \pm 1.12_{d}$

Note. Data are expressed as mean ± SD. Different lowercase superscript letters within the same row indicate statistically significant differences among treatments based on Tukey's HSD multiple comparison test ($\alpha = 0.05$). Note: The nutrient contents of BSF frass, *T. molitor* frass, and *T. commodus* frass are expressed as g/kg based on laboratory analysis, whereas the chemical fertilizer values represent the manufacturer's guaranteed analysis (%) for the commercial NPK 15:15:15 formulation. Note: Total organic matter (TOM) is the percentage of organic material in the sample.

stem diameter (7.94 ± 0.58 mm), while chemical fertilizer application resulted in a moderate stem diameter (10.32 ± 0.47 mm). The control plants showed the smallest stem diameter (2.80 ± 0.50 mm), highlighting the role of nutrient inputs in stem development.

Root growth parameters showed a similar pattern. The maximum horizontal spread of the entire root system, measured at its widest point, was referred to as root width. The longest roots were recorded in plants treated with *H. illucens* (48.06 ± 1.00 mm) and *T. molitor* frass (46.07 ± 0.58 mm), whereas *T. commodus* frass produced shorter roots (28.20 ± 0.06 mm). Chemical fertilizer treatment resulted in a root length of 39.98 ± 1.13 mm, which was significantly greater than the control (19.65 ± 1.13 mm). Root width was highest in *H. illucens*–treated plants (28.55 ± 2.39 mm), followed by *T. molitor* (22.01 ± 2.36 mm) and chemical fertilizer (20.64 ± 0.92 mm). The narrowest roots were observed in the control treatment (2.96 ± 0.92 mm).

3.4. Post-harvest biomass measurement

Post-harvest fresh and dry biomass changed significantly among treatments (Table 4). Plants treated with *Hermetia illucens* frass recorded the highest fresh biomass (11.64 ± 0.60 g) and dry biomass (4.09 ± 0.36 g), and were statistically comparable to those treated with *Tenebrio molitor* frass for fresh biomass (11.25 ± 1.42 g). In contrast, *Teleogryllus commodus* frass resulted in noticeably lower biomass accumulation (7.48 ± 0.38 g fresh weight and 2.15 ± 0.19 g dry weight). The chemical fertilizer treatment produced

Table 4: Mean ± SD of growth parameters and biomass of *Brassica rapa* subsp. chinensis subjected to different insect frass treatments, chemical fertiliser and control treatment

Brassica rapa subsp. chinensis growth parameters and biomass	*Hermetia illucens*	*Tenebrio molitor*	*Teleogryllus commodus*	Chemical fertiliser	Control
Number of leaves	$10.80 \pm 1.30_{a}$	$8.80 \pm 0.84_{ab}$	$5.60 \pm 1.14_{c}$	$7.4 \pm 0.89_{b}$	$4.2 \pm 0.84_{d}$
Leaf length [mm]	$78.12 \pm 2.80_{a}$	$57.26 \pm 5.46_{b}$	$33.48 \pm 5.48_{c}$	$51.64 \pm 3.39_{b}$	$14.81 \pm 0.64_{d}$
Leaf width [mm]	$43.01 \pm 1.31_{a}$	$38.76 \pm 1.49_{ab}$	$21.56 \pm 2.33_{c}$	$36.53 \pm 1.56_{b}$	$5.87 \pm 0.48_{d}$
Height [mm]	$153.12 \pm 4.24_{a}$	$141.66 \pm 4.59_{ab}$	$118.42 \pm 1.78_{c}$	$133.08 \pm 8.66_{b}$	$67.33 \pm 5.88_{d}$
Stem diameter [mm]	$13.53 \pm 0.43_{a}$	$12.34 \pm 0.24_{a}$	$7.94 \pm 0.58_{c}$	$10.32 \pm 0.47_{b}$	$2.80 \pm 0.50_{d}$
Root length [mm]	$48.06 \pm 1.00_{a}$	$46.07 \pm 0.58_{a}$	$28.20 \pm 0.06_{c}$	$39.98 \pm 1.13_{b}$	$19.65 \pm 1.13_{d}$
Root width [mm]	$28.55 \pm 2.39_{a}$	$22.01 \pm 2.36_{ab}$	$11.32 \pm 1.02_{c}$	$20.64 \pm 0.92_{b}$	$2.96 \pm 0.92_{d}$
Total fresh weight [g]	$11.64 \pm 0.6_{a}$	$11.25 \pm 1.42_{a}$	$7.48 \pm 0.38_{c}$	$10.03 \pm 0.32_{b}$	$4.97 \pm 0.19_{d}$
Total dry weight [g]	$4.09 \pm 0.36_{a}$	$3.61 \pm 0.15_{ab}$	$2.15 \pm 0.19_{c}$	$3.28 \pm 0.59_{b}$	$1.03 \pm 0.07_{d}$

Note. Values are expressed as mean ± SD (n = 5). Means followed by different lowercase letters within the same row are significantly different at $p < 0.05$, based on one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) post-hoc test.

intermediate fresh (10.03 ± 0.32 g) and dry biomass (3.28 ± 0.59 g). Unfertilized control plants exhibited the lowest biomass values (4.97 ± 0.19 g fresh weight and 1.03 ± 0.07 g dry weight), signifying partial growth in the absence of nutrient supplementation.

4. Discussion

The agriculture sector is constantly in search of fertilisers that are eco-friendly yet effective, and in this context, insect-based fertilisers have emerged as a potential alternative. In organic sectors, chemicals with severe disadvantages are restricted or avoided completely, while insect-based fertilisers can be an alternative due to their eco-friendly nature, enhancing biodiversity and soil health. Thus, the current study highlighted the efficacy of different insect-based frass on *B. rapa* subsp. chinensis growth parameters. The results showed several key findings on frass efficacy, such as *T. commodus* leading to significantly reduced growth parameters in *B. rapa* subsp. chinensis. This result is possibly attributed to the NH_4^+ toxicity observed with the application of *T. commodus* frass. Related to *T. molitor* and *T. commodus* frass, *H. illucens* including *T. molitor* frass, with a determined plant height, had a more favourable balance of important nutrients, including nitrogen, phosphorus, and potassium (N: P: K). According to Leghari *et al.* [24], nitrogen is a nutrient element vital for plant development, and it is essential for both protein synthesis and absorption.

Potassium enhances general plant strength and disease resistance, phosphorus supports root development and flowering, and nitrogen boosts leafy growth in various crops, including Helianthus annulus by improving stem width and fat content of the seeds [25]. *Teleogryllus commodus* exhibited the highest nitrogen among all the insect-based fertilisers studied, while other insect frass has a lower amount of nitrogen compared to chemical fertilisers [26]. The nitrogen content of house crickets was determined to be 43.5% of dry body weight in a study by Ref. [27]. However, nitrogen concentration can vary based on the applied substrate, rearing environment, and life stage of the insect. According to Yu *et al.* [28], mealworms have a higher nitrogen concentration at the pupal stage of around 10.2% than at the early stages of development. This aligns with our findings, confirming enhanced nitrogen buildup during the pupal stage. This promotes a circular economy by utilising agricultural waste and reducing dependency on artificial chemicals.

Plant height may also be affected by the microbial diversity associated with insect frass, such as beneficial bacteria, which have been reported to enhance nutrient availability and encourage plant growth through nitrogen fixation and organic matter breakdown, which may be present in black soldier fly frass [29]. However, the microbial composition of the frass was not assessed in the present study. The bioavailability and solubility of nutrients in insect frass can enhance the growth of plants. The frass of *H. illucens* may contain nutrients in forms that are more readily available for plant uptake, leading to improved growth. However, the other treated frass, especially *T. commodus*, has less soluble or bioavailable nutrients, resulting in the reduction of growth [25]. However, nutrient bioavailability and solubility were not directly assessed in the present study. *H. illucens* frass enhanced the growth of vegetables due to the increased supply of nutrients from the frass and the faster release of nutrients resulting from the low carbon-to-nitrogen ratio [30].

Additionally, *H. illucens* frass has beneficial soil improvement properties, enhancing organic matter content, the ability to replace chemical fertilisers, and reducing greenhouse gas emissions [31, 32]. Leaves are an important part of the plant, offering insights into the development and growth behaviour of any plant, while their number is remarkably useful for allocation and overall health of the plant to respond to external stimuli. Additionally, leaves play an important role in photosynthesis to transform light energy into chemical energy, thereby supporting growth and efficiency [33]. Reduction in the number of leaves possibly signifies an adjustment

in the plant physiology to maintain utilisation of the resources or to manage stressors such as drought, pests, and nutrient deficiencies, which can be alleviated by using organic fertilisers [34]. Thus, differences in leaf number can be a useful indicator of the effectiveness of fertilisers in improving plant growth and resilience to environmental challenges.

Similarly, stems also serve as an important indicator of a healthy plant, which helps in the transportation of nutrients from roots to leaves and other parts of the plant. Showing the growth and resilience of the plant, *B. rapa* subsp. chinensis stem diameter changed considerably across treatments [35].

Roots are fundamental to plant health, serving as the main site for water and nutrient uptake. The root length and width of *Brassica rapa* subsp. chinensis changed significantly across treatments, revealing different levels of root development and efficacy in nutrient uptake [34]. This study aligns with our study observing the effects of applying different frass to *B. rapa* subsp. chinensis. *T. commodus* recorded the highest NH_4^+-N (10.30 ± 1.73 g/kg), followed by *T. molitor* (4.76 ± 1.73 g/kg), and the lowest recorded NH_4^+ by *H. illucens* (4.03 ± 1.73 g/kg), indicating that NH_4^+ was not efficiently leached from the soil rhizosphere. This imbalance in nitrogen forms can be detrimental to the growth of plants, as excessive NH_4^+ availability is toxic to plants and disrupts overall development. This is supported by studies showing that the nutrient-rich profile and positive effects on soil health of *H. illucens* frass encourage growth [25, 29]. In a study by Esteves *et al.* [36], the potential agronomic value of *H. illucens* frass as an organic fertiliser in short-cycle crops, specifically, lettuce, was assessed.

The results indicate that maximum production was obtained with the combined use of organic and mineral fertilisation, outperforming frass of *H. illucens*. Beesigamukama *et al.* [37] described that the low nutrient content of *H. illucens* frass poses a challenge, as approximately 44% of nitrogen is lost as ammonia through the waste recycling process by *H. illucens* larvae. The level of ammonia evaporation is affected by substrate pH and temperature, and well-ventilated systems are prone to significant ammonia loss. This can potentially reduce the fertiliser rate of the manure due to the risk of ammonia loss. The negative control, which did not receive external fertilisers, exhibited a higher organic nitrogen concentration of (1,656.79 ± 9.36) mg/kg compared to *H. illucens* frass, underscoring the essential role of elevated total crude fibre in fertilisers for regulating organic nitrogen decomposition and NH_4^+ toxicity. These results may be related to differences in total crude fibre content, which might affect organic nitrogen decomposition and nitrogen preservation in soil.

Even though soil microbial activity and NH_4^+ dynamics were not directly measured in the present study, previous studies have proposed that fertiliser composition may affect these processes [38]. The current study suggested that *H. illucens* improved plant growth including *T. molitor* which were comparable in most of the treatment, while chemical fertilisers and a negative control without fertiliser, due to higher NH_4^+ and a low decomposition rate affecting plant performance while increasing the risk of NH_4^+ toxicity. *Brassica rapa* subsp. *chinensis* is sensitive to high NH_4^+ levels, highlighting the need for careful control of nitrogen sources in fertilisers to avoid detrimental effects on plant health [4]. This innovative *H. illucens* frass emphasises the value of insect frass in encouraging plant growth, especially *H. illucens*, and displays how it can be used as a sustainable agricultural enhancement [29]. *H. illucens* frass were significantly higher values than *T. commodus* frass and chemical fertilizer. In every studied metric, *T. molitor* frass performed much better than both the control and *T. commodus* frass. With the exception of leaf length, which *H. illucens* recorded a considerably larger value for, *T. molitor* and *H. illucens* were statistically equal for the most of growth and biomass characteristics. *H. illucens* outperformed chemical fertilizer in terms of plant height, but *T. molitor* showed no discernible difference between the two treatments.

Despite *T. commodus* frass exhibiting the greatest nitrogen content, excessive amounts of nitrogen may hinder plant growth by disturbing nutritional balance or causing ammonium toxicity when nitrogen supply surpasses plant requirements. However, it might not be possible to draw broad conclusions about the impact of frass on plant growth because the quality of frass can be influenced by the type of insect substrate [14].

5. Conclusion

Hermetia illucens demonstrated strong potential in enhancing overall plant growth and fresh and dry biomass of *B. rapa* subsp. chinensis compared to other studied frass, positive chemical fertilisers and a negative control without any fertiliser. The positive growth response associated with *H. illucens* frass indicates its potential as a sustainable organic input and suggests a possible role in reducing reliance on synthetic chemical fertilisers. In contrast, *T. commodus* frass resulted in reduced plant growth and biomass accumulation, indicating lower efficacy for *B. rapa* cultivation. However, *T. molitor* showed growth results comparable to *H. illucens*, while chemical fertilisers did not show as good results as *H. illucens*. Overall, the effectiveness of insect frass appears to depend on substrate-derived nutrient composition, which influences its suitability as a plant growth amendment. However, since the experiment was carried out under controlled pot culture conditions with a very limited sample number and assessed frass generated from a single feed substrate (broiler small intestine meal), the results should be regarded carefully.

These elements could restrict how broadly the findings can be applied to outdoor settings or to frass grown on different rearing substrates. Further studies are needed, including different substrate availability and the role of symbiotic microbes, to further explore the enduring effects and productivity of plants. This will possibly provide valuable insights to endorse the benefits of frass as a possible alternative to synthetic chemical fertiliser and will contribute to sustainable agriculture.

Data availability

The data that support the findings of this study are available from first author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Funding

The authors gratefully acknowledge the financial support provided by Universiti Sains Malaysia through the Research University Team (RUTeam) Grant Scheme (Grant No. R502-KR-RUT001-0000002140-K134). Ikram Ullah also expresses his sincere appreciation to Universiti Sains Malaysia for supporting his PhD studies through the Graduate Scholarship Scheme.

Acknowledgment

The authors express their sincere gratitude to the School of Biological Sciences and the School of Chemical Sciences, Universiti Sains Malaysia (USM), for providing the facilities and resources that supported the completion of this work.

References

[1] F. Biondi, F. Balducci, F. Capocasa, M. Visciglio, E. Mei, M. Vagnoni, B. Mezzetti & L. Mazzoni, “Environmental conditions and agronomical factors influencing the levels of phytochemicals in brassica vegetables responsible for nutritional and sensorial properties”, Applied Sciences **11** (2021) 1927. https://doi.org/10.3390/app11041927.

[2] X. Zhang, J. Li, L. Shao, F. Qin, J. Yang, H. Gu, & X. Pan, "Effects of organic fertilizers on yield, soil physico-chemical property, soil microbial community diversity and structure of Brassica rapa var. Chinensis", Frontiers in Microbiology **14** (2023) 1132853. https://doi.org/10.3389/fmicb.2023.1132853.

[3] A. Fathi, “Role of nitrogen (N) in plant growth, photosynthesis pigments, and N use efficiency: A review”, Agrisost **28** (2022) 1. https://doi.org/10.5281/zenodo.7438164.

[4] R. Munene, E. Changamu, N. Korir & G.-O. Joseph, “Effect of different nitrogen forms on growth, phenolics, flavonoids, and antioxidant activity in amaranth species”, Tropical Plant Research **4** (2017) 81. https://www.tropicalplantresearch.com/archives/2017/vol4issue1/12.pdf.

[5] D. Agustiyani, R. Agandi, Arinafril, A. A. Nugroho & S. Antonius, “The effect of application of compost and frass from black soldier fly larvae (Hermetia illucens L.) on growth of pakchoi (Brassica rapa L.)”, IOP Conference Series: Earth and Environmental Science **762** (2021) 012036. https://doi.org/10.1088/1755-1315/762/1/012036.

[6] H. Shaji, V. Chandran & L. Mathew, “Organic fertilizers as a route to controlled release of nutrients”, in *Controlled Release Fertilizers for Sustainable Agriculture*, F. B. Lewu, T. Volova, S. Thomas & K. R. Rakhimol (Eds.), Elsevier, 2021, pp. 231–245. https://doi.org/10.1016/B978-0-12-819555-0.00013-3.

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

[8] A. Mie, H. R. Andersen, S. Gunnarsson, J. Kahl, E. Kesse-Guyot, E. Rembiałkowska, G. Quaglio & P. Grandjean, “Human health implications of organic food and organic agriculture: A comprehensive review”, Environmental Health **16** (2017) 111. https://doi.org/10.1186/s12940-017-0315-4.

[9] S. Kumar, A. Sharma, V. K. Sharma, K. G. Rosin & D. Kumar, “Enhancement of apple (Malus domestica) productivity and soil health through organic fertilization and bio-inoculants under north-western Himalayan region of India”, Indian Journal of Agricultural Sciences **88** (2018) 1463. https://doi.org/10.56093/ijas.v88i9.83516.

[10] H. Ilahi, K. Hidayat, M. Adnan, F. ur Rehman, R. Tahir, M. S. Saeed, S. W. A. Shah & M. D. Toor, “Accentuating the impact of inorganic and organic fertilizers on agriculture crop production: A review”, Indian Journal of Pure & Applied Biosciences **9** (2021) 36. https://doi.org/10.18782/2582-2845.8546.

[11] I. Ullah, M. S. Khan & H. Abu Hasan, “A review of sustainable solution using black soldier fly larvae and their role in converting organic waste into bio-based resources”, Serangga **30** (2025) 338. https://doi.org/10.17576/serangga-2025-3003-23.

[12] I. Ullah, A. B. A. Khair, M. S. Khan, S. Badshah, E. Ibáñez-Arancibia, M. A. Khan, M. ur Rehman, R. De los Ríos-Escalante, M. Attaullah, & F. Badshah, "Comparative efficacy of black soldier fly (Hermetia illucens) frass derived from animal-based and plant-based wastes on nitrification rate and nitrate uptake in Amaranthus dubius", Journal of Animal and Plant Sciences **36** (2026) 104 https://doi.org/10.36899/JAPS.2026.1.0009.

[13] A. van Huis & D. G. A. B. Oonincx, “The environmental sustainability of insects as food and feed: A review”, Agronomy for Sustainable Development **37** (2017) 43. https://doi.org/10.1007/s13593-017-0452-8.

[14] H. Kagata & T. Ohgushi, “Positive and negative impacts of insect frass quality on soil nitrogen availability and plant growth”, Population Ecology **54** (2012) 75. https://doi.org/10.1007/s10144-011-0281-6.

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

[16] E. A. Ferruzca-Campos, A. K. Rico-Chavez, R. G. Guevara-González, M. Urrestarazu, T. P. L. Cunha-Chiamolera, R. Reynoso-Camacho & R. Guzmán-Cruz, “Biostimulant and elicitor responses to cricket frass (Acheta domesticus) in tomato (Solanum lycopersicum L.) under protected conditions”, Plants **12** (2023) 1327. https://doi.org/10.3390/plants12061327.

[17] D. Houben, G. Daoulas, M.-P. Faucon & A.-M. Dulaurent, “Potential use of mealworm frass as a fertilizer: Impact on crop growth and soil properties”, Scientific Reports **10** (2020) 4659. https://doi.org/10.1038/s41598-020-61765-x.

[18] J. R. Okalebo, K. W. Gathua & P. L. Woomer, *Laboratory Methods of Soil and Plant Analysis: A Working Manual*, 2nd ed., SACRED Africa, Nairobi, Kenya, 2002. https://erepository.uonbi.ac.ke/items/cd107167-8d1c-4637-bb14-ed80e640762b.

[19] J. Murphy & J. P. Riley, “A modified single solution method for the determination of phosphate in natural waters”, Analytica Chimica Acta **27** (1962) 31. https://doi.org/10.1016/S0003-2670(00)88444-5.

[20] S. S. Nielsen, “Determination of moisture content”, in *Food Analysis Laboratory Manual*, Springer, New York, USA, 2010, pp. 17–27. https://link.springer.com/chapter/10.1007/978-1-4419-1463-7_3.
[21] D. K. Kundu & J. K. Ladha, “Efficient management of soil and biologically fixed N_2 in intensively-cultivated rice fields”, Soil Biology and Biochemistry **27** (1995) 431. https://doi.org/10.1016/0038-0717(95)98615-U.
[22] A. Khan, M. A. Khan, M. Adnan, I. Ullah, R. Shahzad, H. S. Younas, M. U. Rehman, H. Zheng, S. Tian & M. U. Hassan, “Carbon sequestration and sustainable soil management”, in Climate Smart Agriculture for Future Food Security, Springer Nature, Singapore, 2025, pp. 37–63. https://doi.org/10.1007/978-981-96-4499-5_2.
[23] E. K. Bünemann, G. Bongiorno, Z. Bai, R. E. Creamer, G. De Deyn, R. De Goede & L. Brussaard, "Soil quality–A critical review", Soil biology and biochemistry **120** (2018) 105. https://doi.org/10.1016/j.soilbio.2018.01.030.
[24] S. J. Leghari, N. A. Wahocho, G. M. Laghari, A. H. Laghari, G. M. Bhabhan, K. H. Talpur, T. A. Bhutto, S. A. Wahocho & A. A. Lashari, “Role of nitrogen for plant growth and development: A review”, Advances in Environmental Biology **10** (2016) 209. https://www.researchgate.net/publication/309704090_Role_of_Nitrogen_for_Plant_Growth_and_Development_A_review.
[25] C. H. Lalander, J. Fidjeland, S. Diener, S. Eriksson & B. Vinnerås, “High waste-to-biomass conversion and efficient Salmonella spp. reduction using black soldier fly for waste recycling”, Agronomy for Sustainable Development **35** (2015) 261. https://doi.org/10.1007/s13593-014-0235-4.
[26] H. K. Ravi, A. Degrou, J. Costil, C. Trespeuch, F. Chemat & M. A. Vian, “Larvae-mediated valorization of industrial, agriculture and food wastes: Biorefinery concept through bioconversion, processes, procedures, and products”, Processes **8** (2020) 857. https://doi.org/10.3390/pr8070857.
[27] T. Ritvanen, H. Pastell, A. Welling & M. Raatikainen, “The nitrogen-to-protein conversion factor of two cricket species: Acheta domesticus and Gryllus bimaculatus”, Agricultural and Food Science **29** (2020) 1. https://doi.org/10.23986/afsci.89101.
[28] X. Yu, Q. He & D. Wang, “Dynamic analysis of major components in the different developmental stages of Tenebrio molitor”, Frontiers in Nutrition **8** (2021) 689746. https://doi.org/10.3389/fnut.2021.689746.
[29] M. T. Gebremikael, N. van Wickeren, P. S. Hosseini & S. De Neve, “The impacts of black soldier fly frass on nitrogen availability, microbial activities, C sequestration, and plant growth”, Frontiers in Sustainable Food Systems **6** (2022) 795950. https://doi.org/10.3389/fsufs.2022.795950.
[30] D. Beesigamukama, S. Subramanian & C. M. Tanga, “Nutrient quality and maturity status of frass fertilizer from nine edible insects”, Scientific Reports **12** (2022) 7182. https://doi.org/10.1038/s41598-022-11336-z.
[31] E. Favoino & D. Hogg, “The potential role of compost in reducing greenhouse gases”, Waste Management & Research **26** (2008) 61. https://doi.org/10.1177/0734242X08088584.
[32] L. Setti, E. Francia, A. Pulvirenti, S. Gigliano, M. Zaccardelli, C. Pane, F. Caradonia, S. Bortolini, L. Maistrello & D. Ronga, “Use of black soldier fly (Hermetia illucens (L.), Diptera: Stratiomyidae) larvae processing residue in peat-based growing media”, Waste Management **95** (2019) 278. https://doi.org/10.1016/j.wasman.2019.06.017.
[33] W. Yamori, "Photosynthesis and respiration", in Plant factory, an indoor vertical farming system for efficient quality food production 2nd ed., Academic Press, 2020, pp. 197–206. https://doi.org/10.1016/B978-0-12-816691-8.00012-1.
[34] C. Wijewardana, A. K. Gonzales, C. M. Vogel & N. E. Martinez, “17α-Ethynylestradiol-induced changes in Brassica rapa during the seedling growth stage”, Agrosystems, Geosciences & Environment **5** (2022) e20258. https://doi.org/10.1002/agg2.20258.
[35] H. Poorter, K. J. Niklas, P. B. Reich, J. Oleksyn, P. Poot & L. Mommer, “Biomass allocation to leaves, stems and roots: Meta-analyses of interspecific variation and environmental control”, New Phytologist **193** (2012) 30. https://nph.onlinelibrary.wiley.com/doi/full/10.1111/j.1469-8137.2011.03952.x.
[36] C. Esteves, P. Fareleira, M. A. Castelo-Branco, I. G. Lopes, M. Mota, D. Murta & R. Menino, “Black soldier fly larvae frass increases the soil’s residual nutrient content and enzymatic activity: A lettuce production trial”, Journal of Insects as Food and Feed **8** (2022) 1431. https://doi.org/10.3920/JIFF2022.0005.
[37] D. Beesigamukama, B. Mochoge, N. K. Korir, K. K. M. Fiaboe, D. Nakimbugwe, F. M. Khamis, S. Subramanian, M. M. Wangu, T. Dubois, S. Ekesi & C. M. Tanga, “Low-cost technology for recycling agro-industrial waste into nutrient-rich organic fertilizer using black soldier fly”, Waste Management **119** (2021) 183. https://doi.org/10.1016/j.wasman.2020.09.043.
[38] D. P. Bebber & V. R. Richards, “A meta-analysis of the effect of organic and mineral fertilizers on soil microbial diversity”, Applied Soil Ecology **175** (2022) 104450. https://doi.org/10.1016/j.apsoil.2022.104450.