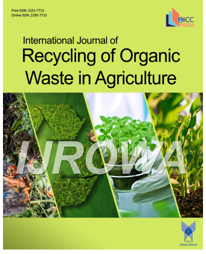

Volume 14, Issue 2, 142520 (1-11)

International Journal of Recycling Organic Waste in Agriculture (IJROWA)

https://doi.org/10.57647/ijrowa-szpn-4w15

Impact of combination of vermicompost and insect frass on long bean growth and productivity at urban farming

Ramadhani Eka Putra[1,*], Ananda Cita Alifah Setiawan[1], Sartika Indah Amalia Sudiarto[1], Ida Kinasih[2]

[1]*Agricultural Engineering Study Program, School of Life Sciences and Technology, Institut Teknologi Bandung, Indonesia.*
[2]*Faculty of Sciences and Technology, Department of Biology, Universitas Islam Negeri Sunan Gunung Djati Bandung, Indonesia.*

[*]**Corresponding author:** ramadhaniputra@itb.ac.id

Original Research

Received:
29 February 2024
Revised:
9 August 2024
Accepted:
12 November 2024
Published online:
15 November 2024

Abstract:

Purpose: Urban farming is experiencing rapid growth and is believed to be a potential solution to future sustainable food production needs. In tropical regions, highly nutritious legumes are a common crop in urban farming. However, most production still highly depends on synthetic fertilizers and manure with high carbon footprints. One possible solution to this issue is the application of fertilizer. This study aimed to find an alternative to synthetic fertilizer for legumes grown in containers in urban farming setups.

Method: In this study, several fertilizers were applied to the long bean (*Vigna sinensis* L.) grown in a container at an urban farming setup. The fertilizers used included synthetic fertilizer, manure, vermicompost, insect frass (produced by black soldier fly larvae fed on municipal wastes), and a combination of vermicompost and insect frass. The parameters observed were the long bean's growth, productivity, and yield quality.

Results: The application of insect frass improves the growth medium chemical, physical, and biological characteristics. However, applying vermicompost produced better growth, productivity, and yield quality than insect frass. Combining vermicompost and insect frass with a ratio 1:1 produced higher plant (281 cm), more average pod numbers per plant (17.33), and the highest average yield per plant (273.13 gram).

Conclusion: Providing vermicompost and insect frass originating from municipal waste could replace synthetic fertilizer and manure to improve the sustainability of urban farming. Combining both materials could produce a synergetic effect, further enhancing the growth and yield of long beans.

Keywords: Carbon footprint; Low input farming; Municipal waste management; Organic fertilizer; Sustainable

1. Introduction

The growing population in the cities raises significant sustainability concerns regarding food security. Traditional methods of supplying food from agricultural and rural areas can increase carbon footprint. Concerns about the high carbon footprint's potential negative impact on climate change and sustainability drive the development of alternative food systems. Urban farming emerges as a standard approach aimed at reducing the carbon footprint while providing a healthy food source for the local population.

However, a study by Hawes et al. (2023) showed that the carbon footprint of urban farming could be higher than that of conventional agriculture, primarily due to high input outside the system. Manure and synthetic chemical fertilizers are primary inputs from outside the urban farming system. To reduce the carbon footprint, it is necessary to apply fertilizers that could be produced by urban farming, like fertilizer originating from municipal wastes. There are two promising approaches to producing high-quality organic fertilizer from municipal wastes: vermicomposting, which produces vermicompost, and insect farming, which produces insect frass.

Vermicomposting, although mainly applied to upcycling manure, has excellent potency to valorized urban organic waste management Sim and Wu (2010), Singh et al. (2011), Alshehrei and Ameen (2021), and Khalid et al. (2023), which could be carried out indoors and outdoors (Enebe and Erasmus, 2023). Vermicompost is the final product of decomposition and stabilization of organic wastes by vermicomposting (Ramnarain et al., 2019; Xie et al., 2023). Vermicompost has been considered a cost-effective fertilizer as part of a more sustainable agriculture system Schroder et al. (2021), Ducasse et al. (2022), and Katiyar et al. (2023) with better quality than classical composting (Tognetti et al., 2005). This material is known to be rich in plant nutrients as growth-promoting substances Krishnamoorthy and Vajranabhaiah (1986), Canellas et al. (2002), and Pattnaik and Reddy (2010) while improving the physical condition of the growth medium (Hanc and Dreslova, 2016). However, there are some concerns about the effectiveness of the application of the vermicomposting method for municipal waste management, such as (1) limitation on the types of waste that could be decomposed by earthworm as most studies only applied food wastes, green wastes, or paper individually Wani et al. (2013), Hanc and Pliva (2013), Soobhany et al. (2015), and Birutha et al. (2020) with few studies on mix wastes Hrebeckova et al. (2019) and EJAB (2020), (2) slow rate of decomposition, and (3) complexity of process to maintain earthworm lifecycle (Hanc et al., 2017; Lohri et al., 2017). Thus, the production cost of vermicompost is considered higher, and its application as a primary fertilizer for urban farming could be limited.

Another approach is applying valorization of organic wastes by insect larvae, which was developed as an option for organic fraction of municipal wastes (OFMW) treatment with the possibility of implementing a circular economy (Girotto and Cossu, 2019; Mak et al., 2020). One of the best insects for this purpose is the black soldier fly (BSF) (*Hermetia illucens*). Black soldier fly larvae can consume varied types of organic wastes, have high consumption and decomposition rates, produce biomass that is high in protein, lipid, energy, and amino acid that fulfill the requirement for animal feed and are easy to maintain, and have low maintenance expenses (Joly and Nikiema, 2019; Singh and KKumari, 2019). This characteristic made BSFL highly applicable to the management of OFMW, especially in developing countries and regions (Salam et al., 2021). Valorization of organic wastes produces a waste product called insect frass, consisting of the dead part of the insect, exoskeletons, remaining food material, and feces. This material contains varied plant nutrients with high potential as fertilizer or organic soil amendment (Barragan-Fonseca et al., 2022; Garttling and Schulz, 2022). The weight of the frass produced could exceed 33% of the original substrate, depending on the substrate type (Basri et al., 2022). Thus, this product is relatively easy to produce in large numbers, which could reduce the price. However, the effectiveness of applying insect frass to crops varies from a negative impact on growth to improving productivity.

In this study, the frass was tested on the long bean (*Vigna sinensis*), which, to our knowledge, is a legume that has never been studied before. The hypothesis tested was that combining vermicompost and insect frass will benefit both soil and plant-examined characteristics. This study could be considered an initial step towards a wider-scale study of the integration of OFMW management and urban farming, especially in developing and early-developed regions.

2. Materials and methods

Study site

The study was conducted at a community urban farming area in the Eastern part of Bandung City, West Java, Indonesia. The location is on the geographic coordinates of 0655′ 25S and 10742′ 13E and is at 684 m above sea level. The study area had a daily temperature of 23.1 – 30.4 ºC (average 25.6 ºC) and humidity between 60 to 80%, which is suitable for the optimum growth of long beans group (Rinaldi et al., 2023).

Fertilizer preparation

This study applied four types of fertilizers: vermicompost, insect frass of black soldier fly (*Hermetia illucens*), goat manure, and commercial synthetic fertilizer, and separated into eight study groups. Vermicompost originated from a local commercial worm farm. Insect frass was produced by the bioconversion process of food waste by black soldier fly larvae conducted by local waste management facilities. Goat manure and synthetic fertilizer were purchased from a local farm shop.

The study groups of this study were:

(1) P1 – control negative group (only soil without application of fertilizer)

(2) P2 – soil with the application of vermicompost

(3) P3 – soil with the application of insect frass

(4) P4 – soil with the application of a combination of vermicompost and insect frass (1:1)

(5) P5 – soil with the application of a combination of vermicompost and insect frass (3:1)

(6) P6 – soil with the application of a combination of vermicompost and insect frass (1:3)

(7) P7 – control positive group (soil with application of synthetic fertilizer)

(8) P8 – soil with application of goat manure

The total growth medium of each group was 30 kg. Each study group was replicated three times. The reference of fertilizer doses based on the previous study, such as

a. The maximum application of vermicompost was 900 grams per container (Dermawan, 2020).

b. The maximum application of insect frass was 330 grams per container (Muhadat, 2021).

c. The maximum application of goat manure was 750 grams per container (Su'ud and Habiba, 2022).

d. The maximum application of synthetic fertilizer was 6.67 grams per container (Hasnelly and Subagiono, 2019).

The dose of fertilizer is shown in Table 1.

Long bean cultivation

Organic fertilizers were mixed evenly with the alluvial soil that dominated the study area's soil. About 30 kg of the mixture was moved into a planting container (60 cm × 50 cm × 50 cm) and kept under plastic cover for seven days. On the other hand, the application of synthetic fertilizer During this process, the field capacity of the growth medium was calculated as a reference for irrigation. After a week, two long bean seeds were planted inside each container, and the containers were arranged randomly (Fig. 1).

Plants were watered twice a day, and weed control was

Table 1. Fertilizer doses of study groups.

Study Group	Fertilizer regime	Fertilizer content	Dose (gram per container)
P1		No fertilizer	-
P2		Vermicompost	900
P3		Insect frass	330
P4	Mixing of vermicompost and insect frass (1:1)	Vermicompost Insect frass	450 165
P5	Mixing of vermicompost and insect frass (3:1)	Vermicompost Insect frass	675 82.5
P6		Vermicompost	225
		Insect frass	247.5
P7		Synthetic fertilizer	6.67
P8		Goat manure	750 gram

conducted manually. Pest control was using physical and natural pest management. The climbing rod was installed three weeks after planting. The first harvest was performed 56 – 60 days after planting and conducted weekly for three weeks.

Observed variables

The observed variables were (1) growth medium condition, (2) growth performance, and (3) harvest quantity and quality (Table 2).

Soil samples

Soil samples were taken from soil kept under clear plastic for 7 days and at the first harvest. All the soil originated from the container for plant growth. The samples were collected by soil ring sampler at a 0 – 30 cm depth. About 5 samples were collected randomly from each study group. The soil was kept in an airtight plastic container (Lockand-Lock). The Soil sample was the subject of analysis on soil physical, chemical, and biological characteristics.

Bulk density

The gravimetric method measured the soil samples as the soil was kept in the oven at 105 ºC for 24 hours. The weight of the dried soil was measured by analytical balance to the nearest milligram and used the calculated bulk density by formula (Table 2)

$$\text{Bulk density} = \frac{\text{soil dry weight} - \text{weight of soil sampler}}{\text{volume of soil sampler}}$$

Soil porosity

Soil samples were the subject of soil density measured by the density bottle method (ASTM Designation D 854-06, 2007; IS:2720-Part 3/sec 1, 1980; BS: 1377-Part 2, 1990). From each growth medium, three samples were used, and the data on soil density was used to calculate soil porosity by formula (Table 2)

$$\text{Soil porosity} = 1 - \frac{\text{Bulk density}}{\text{Soil density}}$$

C-organic

C-organic of soil samples was determined by Walkley and Black method (Network, 2019). In this method, 0.5 gram

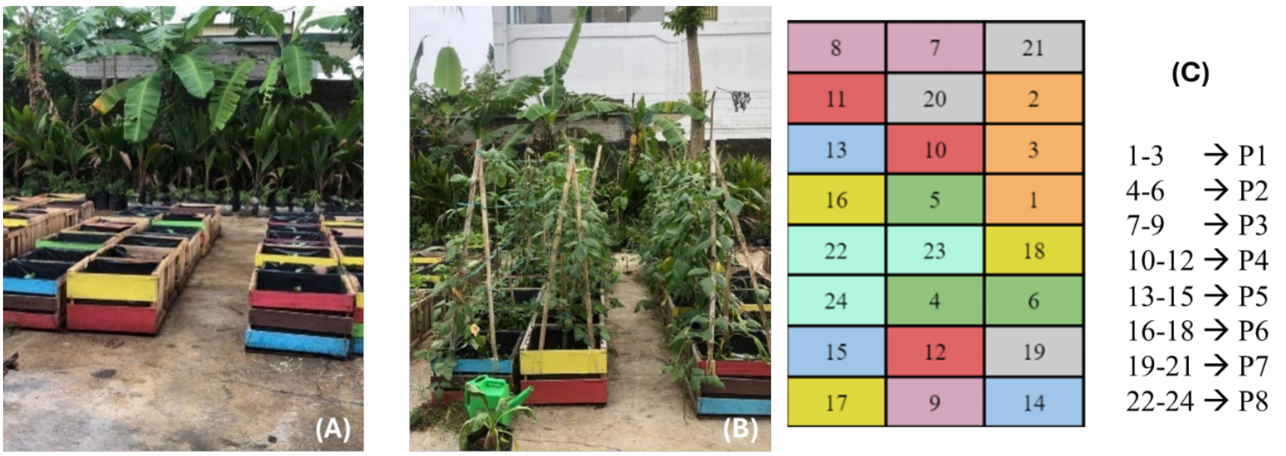

Figure 1. (A) Container prior to planting of long beans, (B) Container with long beans ready to be harvested, (C) Arrangement of container position with different fertilizer regimes.

Table 2. Summary of observed variables and data collection method.

Variables	Method
Growth medium condition	
Bulk density	$\frac{(\text{soil dry weight}-\text{weight of ring sampler})}{\text{volume of ring sampler}}$
Porosity	$1-\frac{\text{Bulk density}}{\text{Soil density}}$
Numbers of soil microbes	Total Plate Count (TPC) by spread method on NA medium
C-organic	Walkley and Black method
N-total	Kjedahl method
P_2O_5	Olsen Method
K_2O_5	Measured by AAS
Growth performance	
Plant height (cm)	Measured by tape measurement
Number of leaves	All mature leaves were counted
Flower numbers	Total numbers of flowers produced by plant
Harvested products	
Number of pods	Number of marketable fruits
Pods weight (g)	Weight of marketable fruits
Pods length (cm)	Length of marketable fruits

soil sample was dissolved with a mixture of 5 mL $K_2Cr_2O_7$ and 10 mL H_2SO_4, heated by hotplate, and then cooled at room temperature. After the solution had cooled, the solution was mixed with 5 mL H_3PO_4 and 50 mL distilled water. The final solution was then titrated with 0.5 M $FeSO_4$, using a burette, until the color changed into a clear green. The C-organic of soil was calculated as the difference between the volume of the $FeSO_4$ solution used for the soil sample and that of the soil sample without (blank).

Total nitrogen, phosphorous, and potassium content

Growth mediums were subject to the test on the availability of significant plant nutrients (nitrogen, phosphorous, and potassium). The total nitrogen of soil samples was measured by Kjedhal method FAO (2021a), while soil available phosphorous was measured by Olsen method FAO (2021b), and potassium was measured using Atomic Absorption Spectrophotometer (400 Perkin Elmer).

Microbial density

The soil samples were collected in sterilized sample vials, labeled based on the fertilizer regime, and then transferred to the laboratory for microbial analysis. The density of soil microorganisms was determined by dilution spread plate technique with nutrient agar (NA) and Potato Dextrose Agar (PDA) as the chosen media for bacteria and fungi growth (Akande and Adekayode, 2019).

Plant height

Plant height was defined as the distance between the plant's tip (highest point) and the ground surface (Jamil and Kooistra, 2022). The height was manually measured to the nearest mm by a 3 m measuring tape. All plants of all fertilizer regimes were subjected to plant height measurements.

Number of leaves

The number of leaves was calculated to determine the effect of the fertilizer on growth. All matured, and healthy leaves were calculated from all plants of all fertilizer regimes.

Flower numbers

Total flowers were counted from the first flowering period until all flowers were dehiscence. All plants, in total 48 plants, were subjected to this activity.

Yield quality

Yield quality was determined by the number of total marketable pods (unbroken pods) and the weight and length of individual pods. The data was shown as average on pod numbers, pod weight, and pod length. All pods produced by each plant were compiled, and digital scales measured the average yield per plant to the nearest mg (Matrix-TD030).

Statistical analysis

All data were subject to the Normality test at the confidence level of 95%. ANOVA tested the normal data set at the confidence level of 95% to detect the significance of differences among data sets. Significant results were further tested by LSD test. The Pearson correlation test tested the correlation between variables. All statistical analyses were conducted using IBM SPSS Statistica Data Editor and Microsoft Excel.

3. Result and discussion

Growth medium: Chemical condition

Fertilizer P6 had the highest N, P_2O_5, and K_2O_5, followed by P5. This result shows the complementary effect of mixing either vermicompost or insect frass, which is not balanced (one part is higher than the other). Both vermicompost and insect frass have been known as organic fertilizers rich in nitrogen, phosphorous, and potassium (Rekha et al., 2018; Beesigamukama et al., 2022; Gebremikael et al., 2020; Antoniadis et al., 2023). This study showed insect frass had higher nitrogen, phosphate, and potassium content than vermicompost. Further, blending both materials significantly improved the content.

The highest C-organic content was recorded from goat manure, followed by the vermicompost group, which related higher organic content resulting from a slower decomposition process (Birutha et al., 2020). High C-organic in vermicompost could be associated with the source of the material, which was cow manure (Muktamar et al., 2022). Among organic-based fertilizers applied in this study, insect frass had the lowest C-organic related to the source of the decomposed material from food waste, which is low in fiber. On the other hand, the highest C/N ratio was recorded from the control group, while the lowest was from P5 and P6. Combining vermicompost and insect frass reduced the C/N ratio of growth medium compared to the application of only vermicompost or insect frass (from an average of 8 to 5), which could be a result of additional nitrogen and activation of mineralization by bacteria (Watson et al., 2021).

Growth medium: Physical condition

The highest porosity at the first harvest was recorded in the P4 (application of vermicompost and insect frass 1:1) group, while the lowest was in the control group. All groups showed improved porosity at harvest except for the P8 group. In general, the application of organic fertilizer improved soil porosity, which is similar to previous study (Xu and Mou, 2016).

Another soil physical variable recorded in this study was bulk density. In general, most groups experienced declining bulk density. Only P2 and P8 showed increasing bulk density. The highest bulk density was recorded in the control group (0.63 gr/cm^3 at the beginning and 0.608 0.63 gr/cm^3 at first harvest), while the lowest in the P4 group at the start of the study (0.45 gr/cm^3) and P6 group at first harvest (0.432 gr/cm^3). On the other hand, the P5 group showed the highest drop in bulk density (Table 3). The growth medium of all groups was considered fertile as the bulk density was below 1.0 g/cm^3 (Li et al., 2019).

Soil bulk density is related to water, air, and space availability, as this variable is used to assess soil compactness. This variable is related to the soil moisture, soil porosity, and hydraulic conductivity Sequeira et al. (2014) and Ilek et al. (2017) in which the factors that influenced soil quality and productivity (Lestariningsih and Hairiah, 2013; Xu et al., 2016; Yang et al., 2016). Studies showed that vermicomposting is a coarse material that increases available space for air and water in the soil (Ibrahim et al., 2015; Singh et al., 2017). This study showed the impact of insect frass on decreasing soil bulk density, which was hardly reported in previous studies. In this study, combined vermicompost and insect frass significantly reduced the soil bulk density, showing the complementary effect of both materials. Increasing bulk density of P2 (only vermicompost) and P8 groups, although non-significant, could be related to the loss of porosity from particle runoff, slow degradation of goat manure, and irregular dry and wet periods of the soil. However, further studies are necessary to determine the cause of the increasing bulk density of organic fertilizer-treated soil.

Growth medium: Biological condition

The microbial population inside the soil influences plant growth productivity and plant health. Diverse and abundant microbial life may improve the nutrient availability for plants and act as a protector from pests and diseases. At the beginning of this study, the highest microbial density was recorded in the P3 group, while the lowest was in the control group. At the first harvest, the highest microbial density was recorded in the P5 group and the lowest in the P8 group. In general, only P3 and P8 showed a decrease in microbial density (Table 3). Studies showed the improvement of soil

Table 3. Chemical, physical, and biological properties of growth medium.

Fertilizer	Chemical					Physical				Biological	
	N total (gram)	P_2O_5 (gram)	K_2O_5 (gram)	C-Organik (gram)	C/N	Porosity (%)		Bulk Density (gram/cm^3)		Microbial density ($\times 10^6$ CFU/mL)	
						7 days	first harvest	7 days	first harvest	7 days	first harvest
P1	69	54	10.2	600	8.696	76.22 ± 1.4^a	77.05 ± 1.3^a	0.630 ± 0.04^a	0.608 ± 0.04^a	0.17	1.48
P2	86.37	64.71	20.19	713.04	8.256	80.31 ± 3.0^a	80.12 ± 2.1^a	0.522 ± 0.08^b	0.527 ± 0.06^b	0.30	2.19
P3	93.366	65.271	30.882	683.226	7.318	81.22 ± 1.2^a	82.36 ± 1.2^a	0.498 ± 0.03^c	0.468 ± 0.03^c	4.08	2.28
P4	81.183	59.636	20.541	698.133	8.599	83.04 ± 1.1^a	83.12 ± 1.6^a	0.450 ± 0.03^d	0.447 ± 0.04^d	0.63	10.13
P5	127.643	77.119	50.948	705.587	5.528	81.18 ± 0.6^a	82.45 ± 1.1^a	0.499 ± 0.02^c	0.465 ± 0.03^c	1.29	11.4
P6	137.232	80.217	61.464	690.68	5.033	82.69 ± 1.3^a	83.69 ± 1.4^a	0.459 ± 0.04^d	0.432 ± 0.04^e	2.13	5.08
P7	70.001	55.001	11.201	600	8.571	80.05 ± 4.8^a	80.97 ± 4.1^a	0.529 ± 0.13^b	0.504 ± 0.11^f	0.38	0.77
P8	112.866	68.946	40.782	849.45	7.526	79.74 ± 3.4^a	79.44 ± 3.4^a	0.537 ± 0.09^e	0.545 ± 0.09^g	0.82	0.39

The different letters showed significant data at $P < 0.05$.

microbial density after soil amendment with vermicompost Lv et al. (2020) and insect frass (Gebremikael et al., 2020; Watson et al., 2021; Barragan-Fonseca et al., 2022; Zande et al., 2024). This study further showed the complementary effect of combining vermicompost with insect frass on the microbial density of the growth medium.

Plant height and number of leaves

Long beans showed different growth performances in response to fertilizer regimes. The effect of the fertilizer regime on plant height was significantly found in group P4 (vermicompost: insect frass (1:1)) and P5 (vermicompost: insect frass (3:1)). On the other hand, application of goat manure as fertilizer basically did not improve the nutritional condition of growth medium for leaves production as the number of leaves produced in group 8 was relatively similar with group 1 in which no additional fertilizer applied (Table 4).

Table 4. Growth performance of long bean under different fertilizer applications.

Fertilizer	Final plant height (cm)	Number of leaves
P1	145.3 ± 42.395^a	51.3 ± 11.015^a
P2	251.7 ± 42.771^b	97.3 ± 26.652^b
P3	237.3 ± 16.506^a	71.0 ± 26.963^b
P4	281.0 ± 32.512^b	96.3 ± 32.716^b
P5	277.3 ± 71.038^b	97.7 ± 4.041^b
P6	202.7 ± 34.776^a	81.0 ± 15.100^b
P7	224.3 ± 33.232^a	66.3 ± 16.000^b
P8	221.0 ± 41.581^a	57.7 ± 4.933^a

The different letters showed significant data at $P < 0.05$.

The growth pattern of height and leaf numbers showed similarity among all fertilizers, indicating nutrients are always available in the growth medium (Fig. 2).
The number of leaves showed a strong positive correlation between plant height and the number of leaves (Fig. 3). This result indicated a similarity in the nutrient requirement for plant height and the number of leaves.
Plant height and leaf production depend on nitrogen availability as the primary nutrient for tissue development. This study showed that vermicompost and the combination of vermicompost and insect frass produced a significantly higher plant than other synthetic fertilizers. Based on the chemical analysis, the amount of nitrogen in organic fertilizer is also higher than that of synthetic chemical fertilizer, which may explain the result.
This result is quite different from other studies, which showed a lower effect of vermicompost than synthetic fertilizer applied in the field condition. However, soil fertilized by vermicompost had higher nitrogen (Yururdurmaz, 2022). It seems that differences in the planting method influenced the effect of vermicompost on the height of varied crops, including legumes, as other studies on pot experiments showed similar results (Kashem et al., 2015; Sadeghipour, 2017). The differences could be related to the mineralization process, which is crucial for nutrient supply from organic fertilizer. A closed system like a pot provides a protected area that allows microbial growth and may improve the speed of the mineralization process.
On the other hand, although the amount of nitrogen in goat manure was higher, the impact on plant height was low, possibly due to the nitrogen not being available to be absorbed by plants. This condition could be related to the characteristics of goat manure inhibiting the rapid mineralization process due to high fiber content (Dalias and Christou, 2020; Zhu et al., 2020). This study also showed that plants fertilized with insect frass with the highest nitrogen, phosphorus, and potassium (P6) had relatively short leaves. The negative impact on the application of high insect frass application rates, especially from black soldier fly, was also reported on maize Alattar et al. (2016) and spinach (Kawasaki et al., 2020).
Gebremikael et al. (2020) showed that most of the black soldier fly frass's nitrogen was immobilized, preventing plants' direct absorption. Even though phosphorous has a beneficial effect on the nitrogen fixation process by legumes Rotaru and Sinclair (2009) and Cabeza et al. (2014), like long bean, excessive amount of phosphorous may trigger oxidative stress, disturb nutrient balance, and alter the interaction between N-fixation bacteria and legume (Khan et al., 2017). On the other hand, excessive potassium may decrease energy efficiency for tissue production Abdel-Wahab (1985) and inhibit magnesium intake, reducing the number of chlorophyll that could stunt plant growth Trankner et al. (2018). However, further studies are needed to test this hypothesis.

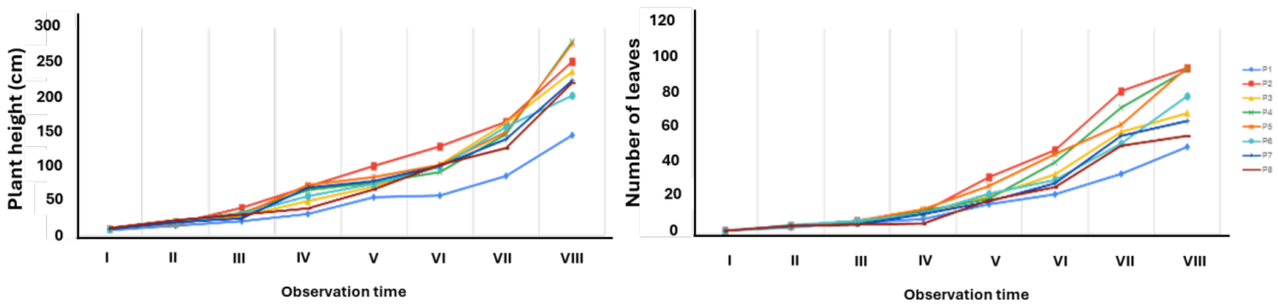

Figure 2. The pattern of plant height and number of leaf growth.

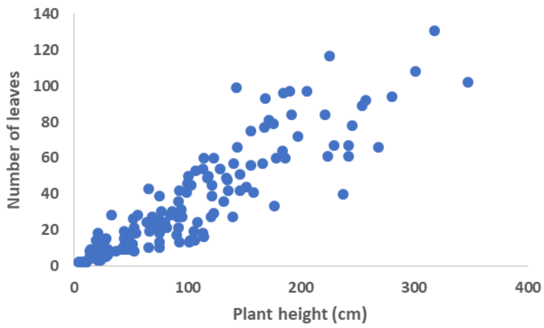

Figure 3. Correlation of the number of leaves and plant height.

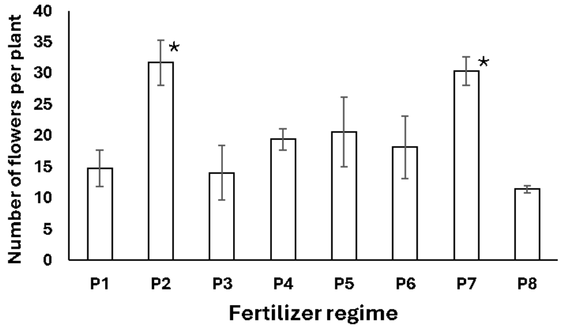

Figure 4. Number of flowers per plant at different fertilizer regimes.

Flower numbers and harvested product

The effect of the fertilizer regime on flower production was more varied as the application of goat manure significantly produced the lowest number of flowers, while the application of only vermicompost and synthetic fertilizer produced considerably more flowers (Fig. 4).

Phosphorus is the primary nutrient for flower production (Khan et al., 2023). Interestingly, plants that received the most phosphorous did not produce the highest flowers. It seems there was a problem with phosphorous acquisition by long beans during cultivation. Since the study was conducting a closed system in the pot, which removed the impact of environmental factors such as leaching, the possible explanation was the acquisition of excess phosphorous to be immobilized by microbes (Zhang et al., 2018). A high C:P ratio (shown in group P4) could enhance phosphorous immobilization by microbes (Kouno et al., 2002). Another possible explanation is that applying insect frass, the combination of vermicompost and insect frass, and goat manure changes the soil characteristics, making discontinued irrigation trigger phosphorous immobilization by bacteria (Yevdokimov et al., 2016). However, further studies are needed to test this hypothesis.

Harvest was conducted three times, and the pod production at P1 and P8 was delayed one week after other groups (data not shown). The highest number of pods per plant was recorded from P2 and P4; however, the pod production was highly varied; thus, no differences were detected among samples. The control group produced the lightest pod, while the heaviest pod was recorded in P8. Groups P1, P2, and P3 produced a significantly shorter long bean than others, albeit the length was still acceptable for the local market. Among groups, the average yield per plant of P2, P4, and P8 was significantly higher than other groups, with the P4 group producing the highest yield. In contrast, the lowest yield was recorded in the P6 group (Table 5).

This study showed the benefit of vermicompost in improving the quality and yield of long beans, as reported by previous studies (Gunawan et al., 2022). Further, the effect was superior to other fertilizers, including insect frass. Insect frass with more nutrient content showed less impact on productivity, which could be related to the immobilization of the nutrient. This condition seems to be overturned when insect frass is combined with vermicompost. It appears that high mineralization, especially nitrogen, of vermicompost provides necessary nutrients for early growth, and a high phosphorous and potassium supply from insect frass improves the condition of the generative stage of long beans. The benefit of combination supports the suggestion of Gebremikael et al. (2020) to overcome the negative effect of N mineralization on insect frass.

Another explanation for the low effect of insect frass on productivity was the low stability of the material. This study used relatively fresh insect frass, which reported stunted growth and negatively affected productivity Song et al. (2021), while aged insect frass showed significant improvement in the growth and productivity of the crop (Korir et al., 2021). Vermicompost is known as a material that can

Table 5. Long bean harvest yield and quality under different fertilizer applications.

Fertilizer	Average pod numbers per plant	Average pod weight (gram)	Average pod length (cm)	Average yield per plant (gram)
P1	7.33 ± 4.04^{a}	21.27 ± 2.56^{a}	59.43 ± 3.53^{a}	75.50 ± 23.18^{a}
P2	17.0 ± 9.17^{ab}	32.82 ± 2.84^{ab}	68.41 ± 4.66^{a}	237.83 ± 192.4^{b}
P3	13.0 ± 7.21^{ab}	31.01 ± 5.76^{ab}	67.75 ± 8.67^{abc}	146.68 ± 97.77^{a}
P4	17.33 ± 4.04^{ab}	33.09 ± 2.21^{b}	70.01 ± 7.75^{bc}	273.13 ± 211.79^{b}
P5	14.67 ± 2.89^{ab}	30.43 ± 7.17^{b}	69.43 ± 10.29^{c}	140.11 ± 40.83^{a}
P6	$9.67a \pm 7.23^{a}$	31.21 ± 2.81^{b}	70.59 ± 9.33^{c}	88.73 ± 58.30^{a}
P7	$11.67a \pm 4.58^{b}$	27.93 ± 8.28^{b}	71.92 ± 11.97^{c}	96.56 ± 34.44^{a}
P8	$9.17a \pm 3.06^{b}$	37.60 ± 12.80^{b}	73.27 ± 10.39^{c}	182.48 ± 100.96^{b}

Different letters indicated significant data on the significance level of 95%

accelerate the stabilization of varied organic matters Frederickson et al. (1997), Kaviraj (2003), Tanuja et al. (2019), and Askari et al. (2020), which may improve the quality of insect frass through stabilization (Lopes et al., 2022).

Implication of the study

This study showed the promising application of vermicompost and insect frass as fertilizer for urban farming, especially for urban agriculture, that applies planting inside pots and other containers. Vermicompost and insect frass could be produced solely from municipal wastes, which is beneficial for urban areas that lack a source of high-fiber organic material that is usually used to produce compost. Further, this study also showed the possibility of integrating urban farming into local waste management programs by applying earthworms and insects as decomposers, which may reduce the carbon footprint of urban agriculture (Hawes et al., 2023). Moreover, both vermicomposting and insect bioconversion processes produce less greenhouse gases than composting (Ermolaev et al., 2019; Yasmin et al., 2022; Rossi et al., 2024). On the other hand, this procedure allows the development of more environmentally friendly and emission-less urban farming.

4. Conclusion

This study showed that vermicompost and insect frass could be applied as alternatives to synthetic fertilizers to improve the sustainability of the farming system. Further, it could also replace manure, which usually has a high carbon footprint. In general, soil that received insect frass (originated from black soldier fly larvae) had more nitrogen, phosphorous, potassium, higher porosity, lower bulk density, and higher microbial density. However, growth performance, productivity, and yield quality were lower than plants that received only vermicompost, indicating the instability of the material as organic fertilizer. Combining both materials improved the growth and productivity, especially at 1:1 (weight/weight), which indicated the synergy between vermicompost and insect frass.

Acknowledgment

Authors thank Warung Kebon Community Farm for providing the cultivation facility. This study was partially funded by the Economic Recovery Community Service Grant 2022 and Riset Uggulan ITB 2024 Number 959/IT1.B07.1/TA.00/2024, both received by the corresponding author.

Authors contributions

Conceptualization: R.E. Putra; Methodology: S.I.A. Sudiarto; Data collection: A.C.A. Setiawan; Formal analysis: A.C.A. Setiawan, S.I.A. Sudiarto, I. Kinasih; Writing-original draft: A.C.A. Setiawan; Writing-review & editing: R.E. Putra, S.I.A. Sudiarto, I. Kinasih; Scientific analysis: R.E. Putra, I. Kinasih; Preparation of final draft: R.E. Putra, I. Kinasih; Funding acquisition: R.E. Putra. All authors approved the manuscript.

Availability of data and materials

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

Conflict of interests

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 paper.

References

Abdel-Wahab S (1985) Potassium nutrition and nitrogen fixation by nodulated legumes. *Fert Res* 8:9–20. DOI: https://doi.org/10.1007/BF01048903.

Akande GM, Adekayode FO (2019) Identification of soil microbial population under different land use. *Trop Plant Res* 6 (1): 90–100. DOI: https://doi.org/10.22271/tpr.2019.v6.il.013.

Alattar MA, Alattar FN, Popa R (2016) Effects of microaerobic fermentation and black soldier fly larvae food scrap processing residues on the growth of corn plants (Zea mays). *Plant Sci. Today* 3:57–62. DOI: https://doi.org/10.14719/pst.2016.3.1.179.

Alshehrei F, Ameen F (2021) Vermicomposting: a management tool to mitigate solid waste. *Saudi J Biol Sci* 28:3284–3293. DOI: https://doi.org/10.1016/j.sjbs.2021.02.072.

Antoniadis V, Molla A, Grammenou A, Apostolidis V, Athanassiou CG, Rumbos CI, Levizou E (2023) Insect frass as a novel organic soil fertilizer for the cultivation of spinach (Spinacia oleracea): Effects on soil properties, plant physiological parameters, and nutrient status. *J Soil Sci Plant Nutr* 23:5935–5944. DOI: https://doi.org/10.1007/s42729-023-01451-9.

Askari A, Khanmirzae A, Rezaei S (2020) Vermicompost enrichment using organic wastes: Nitrogen content and mineralization. *Int J Recycl Org Waste Agricult* 9:151–160. DOI: https://doi.org/IJROWA.2020.1885015.1001.

Barragan-Fonseca KY, Nurfikari A, Zande EM van de, Wantulla M, Loon JJA van, Boer W de, Dicke M (2022) Insect frass and exuviae to promote plant growth and health. *Trends Plant Sci* 27 (7): 646–654. DOI: https://doi.org/10.1016/j.tplants.2022.01.007.

Basri NEA, Azman NA, Ahmad IK, Suja F, Jalil NAA, Amrul NF (2022) Potential applications of frass derived from black soldier fly larvae treatment of food waste: A review. *Foods* 11 (17): 2664. DOI: https://doi.org/10.3390/foods11172664.

Beesigamukama D, Subramanian S, Tanga CM (2022) Nutrient quality and maturity status of frass fertilizer from nine edible insects. *Sci Rep* 12:7182. DOI: https://doi.org/10.1038/s41598-022-11336-z.

Birutha M, Karmegam N, Archana J, Selvi BK, Paul JAJ, Balamuralikrishnan B, Chang SW, Ravindran B (2020) Vermiconversion of biowastes with low-to-high C/N ratio into value added vermicompost. *Bioresour Technol* 297:122398. DOI: https://doi.org/10.1016/j.biortech.2019.122398.

Cabeza RA, Liese R, Lingner A, Stieglitz I von, Neumann J, Salinas-Riester G, Pommerenke C, Dittert K, Schulze J (2014) RNA-seq transcriptome profiling reveals that Medicago truncatula nodules acclimate N_2 fixation before emerging P deficiency reaches the nodules. *J Exp Bot* 65:6035–6048. DOI: https://doi.org/10.1093/jxb/eru341.

Canellas LP, Olivares FL, Okorokova-Facanha AL, Facanha AR (2002) Humic acids isolated from earthworm compost enhance root elongation, lateral root emergence, and plasma membrane H+-ATPase activity in maize roots. *Plant Physiol* 130:1951–1957. DOI: https://doi.org/10.1104“%2Fpp.007088.

D ASTM Designation (2007) Standard test method for specific gravity of soil solids by water pycnometer: annual book of ASTM standards. *ASTM, West Conshohocken* 0402:854–06.

Dalias P, Christou A (2020) Nitrogen supplying capacity of animal manures to the soil in relation to the length of their storage. *Nitrogen* 1 (1): 52–66. DOI: https://doi.org/10.3390/nitrogen1010006.

Dermawan H (2020) Effect of vermicompost and organik nitrogen, phosphorous, potassium on growth and productivity of long bean (*Vigna unguiculata var. sesquagpedalis*). *Bachelor degree thesis. Agricultural Faculty, Universitas Islam Riau, Pekanbaru, Indonesia.*, https://repository.uir.ac.id/8755/1/154110417.pdf

Ducasse V, Capowiez Y, Peigne J (2022) Vermicomposting of municipal solid waste as a possible lever for the development of sustainable agriculture. A review. *Agron Sustain Dev* 42:89. DOI: https://doi.org/10.1007/s13593-022-00819-y.

EJAB (2020) Vermicomposting of organic waste with Eisenia fetida increases the content of exchangeable nutrients in soil. *Pak J Biol Sci* 23:501–509. DOI: https://doi.org/10.3923/pjbs.2020.501.509.

Enebe MC, Erasmus M (2023) Vermicomposting technology - A perspective on vermicompost production technologies, limitations and prospects. *J Environ Manage* 345:118585. DOI: https://doi.org/10.1016/j.jenvman.2023.118585.

Ermolaev E, Lalander C, Vinneras B (2019) Greenhouse gas emissions from small-scale fly larvae composting with Hermetia illucens. *Waste Manage* 96:65–74. DOI: https://doi.org/10.1016/j.wasman.2019.07.011.

FAO (2021a) Standard operating procedure for soil nitrogen - Kjeldahl method. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/17a0e476-f796-4608-a869-295a367c0b56/content.

——— (2021b) tandard operating procedure for soil available phosphorus - Olsen method. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/d69a78fc-3ccd-4a9d-a77a-7e729be66c4a/content. Accessed10October2024

Frederickson J, Butt KR, Morris RM, Daniel C (1997) Combining vermiculture with traditional green waste composting systems. *Soil Biol Biochem* 29 (3-4): 725–730. DOI: https://doi.org/10.1016/S0038-0717(96)00025-9.

Garttling D, Schulz H (2022) Compilation of black soldier fly frass analyses. *J Soil Sci Plant Nutr* 22:937–943. DOI: https://doi.org/10.1007/s42729-021-00703-w.

Gebremikael MT, Ranasinghe A, Hosseini PS, Laboan B, Sonneveld E, Pipan M, Oni FE, et al. (2020) How do novel and conventional agri-food wastes, co-products and by-products improve soil functions and soil quality *Waste Manag* 113:132–144. DOI: https://doi.org/10.1016/j.wasman.2020.05.040.

Girotto F, Cossu R (2019) Role of animals in waste management with a focus on invertebrates' biorefinery: an overview. *Environ Dev* 32:100454. DOI: https://doi.org/10.1016/j.envdev.2019.08.001.

Gunawan B, Nisak F, Purwanti S, Nurlina (2022) Increasing productivity long bean plant (*Vigna sinensis L*) with organic vermicompost fertilizer. *Agri Sci* 6 (1): 21–29. DOI: https://doi.org/10.55173/agriscience.v6i1.78.

Hanc A, Castkova T, Kuzel S, Cajthaml T (2017) Dynamics of a vertical-flow windrow vermicomposting system. *Waste Manag Res* 35:1121–1128. DOI: https://doi.org/10.1177/0734242X17725161.

Hanc A, Dreslova M (2016) Effect of composting and vermicomposting on properties of particle size fractions. *Bioresour Technol* 217:186–189. DOI: https://doi.org/10.1016/j.biortech.2016.02.058.

Hanc A, Pliva P (2013) Vermicomposting technology as a tool for nutrient recovery from kitchen biowaste. *J Mater Cycles Waste Man* 15:431–439. DOI: https://doi.org/10.1007/s10163-013-0127-8.

Hasnelly I Purwanto H, Subagiono (2019) Effect of synthetic nitrogen, phosphorous, and potassium fertilizer on growth and productivity of long bean (*Vigna sinensis L.*). *J Sains Agro* 4 (1): 1–9. https://ojs.umb-bungo.ac.id/index.php/saingro/article/view/246/269

Hawes JK, Goldstein BP, Newell JP, Dorr E, Caputo S, Fox-Kamper R, Grard B, et al. (2023) Comparing the carbon footprints of urban and conventional agriculture. *Nat Cities* 1:164–173. DOI: https://doi.org/10.1038/s44284-023-00023-3.

Hrebeckova T, Wiesnerova L, Hanc A (2019) Changes of enzymatic activity during a large-scale vermicomposting process with continuous feeding. *J Clean Prod* 239:118127. DOI: https://doi.org/10.1016/j.jclepro.2019.118127.

Ibrahim MM, Mahmoud EK, Ibrahim DA (2015) Effects of vermicompost and water treatment residuals on soil physical properties and wheat yield. *Int Agrophys* 29 (2): 157–164. DOI: https://doi.org/10.1515/intag-2015-0029.

Ilek A, Kucza J, Szostek M (2017) The effect of the bulk density and the decomposition index of organic matter on the water storage capacity of the surface layers of forest soils. *Geoderma* 285:27–34. DOI: https://doi.org/10.1016/j.geoderma.2016.09.025.

Jamil N, Kooistra G Kootstra L (2022) Evaluation of individual plant growth estimation in an intercropping field with UAV imagery. *Agriculture* 12 (1): 102. DOI: https://doi.org/10.3390/agriculture12010102.

Joly G, Nikiema J (2019) Global experiences on waste processing with black soldier fly (Hermetia illucens): from technology to business. *Iwmi* 16 DOI: https://doi.org/10.5337/2019.214.

Kashem MdA, Sarker A, Hossain I, Islam MdS (2015) Comparison of the effect of vermicompost and inorganic fertilizers on vegetative growth and fruit production of tomato (*Solanum lycopersicum L.*). *Open J Soil Sci* 5:53–58. DOI: https://doi.org/10.4236/ojss.2015.52006.

Katiyar RB, Sundaramurthy S, Sharma AK, Arisutha S, Pratap-Singh A, Mishra S, Ayub R, Jeon BH, Khan MA (2023) Vermicompost: An eco-friendly and cost-effective alternative for sustainable agriculture. *Sustainability* 15 (20): 14701. DOI: https://doi.org/10.3390/su152014701.

Kaviraj SS (2003) Municipal solid waste management through vermicomposting employing exotic and local species of earthworms. *Bioresour Technol* 90:169–173. DOI: https://doi.org/10.1016/S0960-8524(03)00123-8.

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* 12:4920. DOI: https://doi.org/10.3390/su12124920.

Khalid H, Ikhlaq A, Pervaiz U, Wie YM, Lee EJ Lee KH (2023) Municipal waste degradation by vermicomposting using a combination of *Eisenia fetida and Lumbricus rubellus* species. *Agronomy* 13 (5): 1370. DOI: https://doi.org/10.3390/agronomy13051370.

Khan F, Siddique AB, Shabala S, Zhou M, Zhao C (2023) Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. *Plants* 12:2861. DOI: https://doi.org/10.3390/plants12152861.

Khan VM, Ahamad A, Yadav BL, Irfan M (2017) Effect of vermicompost and biofertilizers on yield attributes and nutrient content and it's their uptake of cowpea [*Vigna unguiculata* (L.) Walp.]. *Int J Curr Microbiol App Sci* 6 (6): 1045–1050. DOI: https://doi.org/10.20546/ijcmas.2017.606.120.

Korir AO Anyega Aand NK, Beesigamukama D, Changeh GJ, Nkoba K, Subramanian S, Loon JJA Van, Dicke M, Tanga CM (2021) Black soldier fly-composted organic fertilizer enhances growth, yield, and nutrient quality of three key vegetable crops in Sub-Saharan Africa. *Front Plant Sci* 12:680312. DOI: https://doi.org/10.3389/fpls.2021.680312.

Kouno K, Wu J, Brookes PC (2002) Turnover of biomass C and P in soil following incorporation of glucose or ryegrass. *Soil Biol. Biochem.* 34:617–622. DOI: https://doi.org/10.1016/S0038-0717(01)00218-8.

Krishnamoorthy RV, Vajranabhaiah SN (1986) Biological activity of earthworm casts: An assessment of plant growth promotor levels in the casts. *Proc Anim Sci* 95:341–351. DOI: https://doi.org/10.1007/BF03179368.

Lestariningsih ID, Hairiah WK (2013) Assessing soil compaction with two different methods of soil bulk density measurement in oil palm plantation soil. *Procedia Environ Sci* 17:172–178. DOI: https://doi.org/10.1016/j.proenv.2013.02.026.

Li S, Li Q, Wang C, Li B, Gao X, Li Y, Wu D (2019) Spatial variability of soil bulk density and its controlling factors in an agricultural intensive area of Chengdu Plain, Southwest China. *J Integr Agric* 18 (2): 290–300. DOI: https://doi.org/10.1016/S2095-3119(18)61930-6.

Lohri CR, Diener S, Zabaleta I, Mertenat A, C C Zurbrugg (2017) Treatment technologies for urban solid biowaste to create value products: a review with focus on low- and middle-income settings. *Rev Environ Sci Biotechnol* 16:81–130. DOI: https://doi.org/10.1007/s11157-017-9422-5.

Lopes IG, Yong JWH, Lalander C (2022) Frass derived from black soldier fly larvae treatment of biodegradable wastes. A critical review and future perspectives. *Waste Manage* 142:65–76. DOI: https://doi.org/10.1016/j.wasman.2022.02.007.

Lv M, Li J, Zhang W, Zhou B, Dai J, Zhang C (2020) Microbial activity was greater in soils added with herb residue vermicompost than chemical fertilizer. *Soil Ecol Lett* 2:209–219. DOI: https://doi.org/10.1007/s42832-020-0034-6.

Mak TMW, Xiong X, Tsang DCW, Yu IKM, Poon CS (2020) Sustainable food waste management towards circular bioeconomy: Policy review, limitations and opportunities. *Bioresour Technol* 297:122497. DOI: https://doi.org/10.1016/j.biortech.2019.122497.

Muhadat IS (2021) Black soldier fly frass as alternative solid organic fertilizer on the verticulture of Indian mustard (*Brassica juncea L.*). *Bachelor degree thesis.Faculty of Tarbiyah and Teaching. Universitas Islam Negeri Raden Intan, Lampung, Indonesia.*, https://repository.radenintan.ac.id/14400/

Muktamar Z Riwandi, Hasanudin A, Allsari V (2022) The quality of vermicompost from various sources composted with earthworm *Perionyx* excavates. *IOP Conf Ser: Earth Environ Sci* 1005:012006. DOI: https://doi.org/10.1088/1755-1315/1005/1/012006.

Network Global Soil Laboratory (2019) Standard operating procedure soil organic carbon, Walkley-Black method: Titration and colorimetric method. *Food and Agriculture Organization of the United Nations, Rome.*

Pattnaik S, Reddy MV (2010) Nutrient status of vermicompost of urban green waste processed by three earthworm species— *Eisenia fetida*, *Eudrilus eugeniae*, and *Perionyx excavatus*. *Appl Environ Soil Sci* 2010:1–13. DOI: https://doi.org/10.1155/2010/967526.

Ramnarain YI, Ansari AA, Ori L (2019) Vermicomposting of different organic materials using the epigeic earthworm Eisenia foetida. *Int J Recycl Org Waste Agricult* 8:23–36. DOI: https://doi.org/10.1007/s40093-018-0225-7.

Rekha GS, Kaleena PK, Elumalai D, Srikumaran MP, Maheswari VN (2018) Effects of vermicompost and plant growth enhancers on the exo-morphological features of *Capsicum annum* (Linn.)Hepper. *Int J Recycl Org Waste Agricult* 7:83–88. DOI: https://doi.org/10.1007/s40093-017-0191-5.

Rinaldi FB, Sudiana E, Hardiyati T (2023) Global warming and the phenology of Yard-long Beans (*Vigna unguiculata* subsp. cylindrica (L.) Verdc.). *Interdiscip Int J Conserve Cult* 1 (2): 73–79. DOI: https://doi.org/10.25157/iijcc.v1i2.3514.

Rossi G, Ojha S, Berg W, Herppich WB, Schluter OK (2024) Estimating the dynamics of greenhouse gas emission during black soldier fly larvae growth under controlled environmental conditions. *J Clean Prod* 470:143226. DOI: https://doi.org/10.1016/j.jclepro.2024.143226.

Rotaru V, Sinclair TR (2009) Interactive influence of phosphorus and iron on nitrogen fixation by soybean. *Environ Exp Bot* 66:94–99. DOI: https://doi.org/10.1016/j.envexpbot.2008.12.001.

Sadeghipour O (2017) Comparison of the effects of vermicompost and chemical fertilizers on growth and yield of common bean (Phaseolus vulgaris). *International Conference on Advances in Engineering Sciences: ICAES2017*

Salam M, Alam F, Dezhi S, Nabi G, Shahzadi A, Hassan SU, Ali M, et al. (2021) Exploring the role of black soldier fly larva technology for sustainable management of municipal solid waste in developing countries. *Environ Technol Innov* 24:101934. DOI: https://doi.org/10.1016/j.eti.2021.101934.

Schroder C, Hafner F, Larsen OC, Krause A (2021) Urban organic waste for urban farming: Growing lettuce using vermicompost and thermophilic compost. *Agronomy* 11 (6): 1175. DOI: https://doi.org/10.3390/agronomy11061175.

Sequeira CH, Wills SA, Seybold CA, West LT (2014) Predicting soil bulk density for incomplete database. *Geoderma* 213:64–73. DOI: https://doi.org/10.1016/j.geoderma.2013.07.013.

Sim EYS, Wu TY (2010) The potential reuse of biodegradable municipal solid wastes (MSW) as feedstocks in vermicomposting. *J Sci Food Agric* 90:2153–2162. DOI: https://doi.org/10.1002/jsfa.4127.

Singh A, KKumari (2019) An inclusive approach for organic waste treatment and valorisation using Black Soldier Fly larvae: A review. *J Environ Manage* 251:109569. DOI: https://doi.org/10.1016/j.jenvman.2019.109569.

Singh RP, Singh P, Araujo ASF, Ibrahim M Hakimi, Sulaiman O (2011) Management of urban solid waste: vermicomposting a sustainable option. *Resour Conserv Recycl* 55:719–729. DOI: https://doi.org/10.1016/j.resconrec.2011.02.005.

Singh TDH, Swaroop N, Thomas T, David AA (2017) Effect of different levels of vermicompost on soil physical properties of two cultivars of cabbage (*Brassica oleracea L.*) under Eastern UP (India) conditions. *Int J Curr Microbiol App Sci* 6 (6): 2908–2911. DOI: https://doi.org/10.20546/ijcmas.2017.606.344.

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. DOI: https://doi.org/10.1016/j.jclepro.2020.125664.

Soobhany N, Mohee R, Garg VK (2015) Recovery of nutrient from municipal solid waste by composting and vermicomposting using earthworm *Eudrilus eugeniae*. *J Environ Chem Eng* 3:2931–2942. DOI: https://doi.org/10.1016/j.jece.2015.10.025.

Su'ud M, Habiba (2022) Response on dosage and type of fertilizers on the growth and productivity of long bean (*Vigna sinensis L.*). *Agrotechbiz: J Ilmu Pertanian* 3 (1): 7–13. https://ejournal.upm.ac.id/index.php/agrotechbiz/article/view/268/281

Tanuja S, Nayak SK, Sarangi DN (2019) Growth, yield and biochemical responses of cowpea (*Vigna unguiculata*) to fish silage enriched vermicompost. *Indian J Fish* 66 (1): 138–141. DOI: https://doi.org/10.21077/ijf.2019.66.1.80833-19.

Tognetti C, Laos F, Mazzarino MJ, Hernandez MT (2005) Composting vs. vermicomposting: A comparison of end product quality. *Compost Sci Util* 13:6–13. DOI: https://doi.org/10.1080/1065657X.2005.10702212.

Trankner M, Tavakol E, Jakli B (2018) Functioning of potassium and magnesium in photosynthesis, photosynthate translocation and photoprotection. *Physiol Plant* 163 (3): 414–431. DOI: https://doi.org/10.1111/ppl.12747.

Wani KA, Mamta, Rao RJ (2013) Bioconversion of garden waste, kitchen waste and cow dung into value-added products using earthworm *Eisenia fetida*. *Saudi J Biol Sci* 20:149–154. DOI: https://doi.org/10.1016/j.sjbs.2013.01.001.

Watson C, Schlosser C, Vogerl J, Wichern F (2021) Excellent excrement Frass impacts on a soil's microbial community, processes and metal bioavailability. *Appl Soil Ecol* 168:104110. DOI: https://doi.org/10.1016/j.apsoil.2021.104110.

Xie J, Xia H, Guan M, Huang K, Chen J (2023) Accelerating the humification mechanism of dissolved organic matter using biochar during vermicomposting of dewatered sludge. *Waste Manage* 159:102–113. DOI: https://doi.org/10.1016/j.wasman.2023.01.022.

Xu C, Mou B (2016) Vermicompost affects soil properties and spinach growth, physiology, and nutritional value. *Hort Sci* 51 (7): 847–855. DOI: https://doi.org/10.21273/HORTSCI.51.7.847.

Xu L, He NP, Yu GR (2016) Methods of evaluating soil bulk density: Impact on estimating large scale soil organic carbon storage. *Catena* 144:94–101. DOI: https://doi.org/10.1016/j.catena.2016.05.001.

Yang QY, Luo WQ, Jiang ZC, Li WJ, Yuan DX (2016) Improve the prediction of soil bulk density by cokriging with predicted soil water content as auxiliary. *J Soils Sediments* 16:77–84. DOI: https://doi.org/10.1007/s11368-015-1193-4.

Yasmin N, Jamuda M, Panda AK, Samal K, Nayak JK (2022) Emission of greenhouse gases (GHGs) during composting and vermicomposting: Measurement, mitigation, and perspectives. *Energy Nexus* 7:100092. DOI: https://doi.org/10.1016/j.nexus.2022.100092.

Yevdokimov I, Larionova A, Blagodatskaya E (2016) Microbial immobilization of phosphorus in soils exposed to drying-rewetting and freeze-thawing cycles. *Biol Fertil Soils* 52:685–696. DOI: https://doi.org/10.1007/s00374-016-1112-x.

Yururdurmaz C (2022) Impact of different fertilizer forms on yield components and macro–micronutrient contents of Cowpea (*Vigna unguiculata L.*). *Sustainability* 14 (19): 12753. DOI: https://doi.org/10.3390/su141912753.

Zande EM van de, Wantulla M, Loon JJA van, 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* 495:631–648. DOI: https://doi.org/10.1007/s11104-023-06351-6.

Zhang L, Ding X, Peng Y, George TS, Feng G (2018) Closing the loop on phosphorus loss from intensive agricultural soil: A microbial immobilization solution *Front Microbiol* 9:104. DOI: https://doi.org/10.3389/fmicb.2018.00104.

Zhu Y, Merbold L, Leitner S, Pelster DE, Okoma SA, Ngetich F, Onyango AA, Pellikka P, Bhal KB (2020) The effects of climate on decomposition of cattle, sheep and goat manure in Kenyan tropical pastures. *Plant Soil* 451:325–343. DOI: https://doi.org/10.1007/s11104-020-04528-x.