

Effect of Black Soldier Fly Larvae Frass on the Growth of Pak Choy and Selected Soil Chemical Properties

Soo Tsou Hung¹, Mohamadu Boyie Jalloh², Elisa Azura Azman^{1*}, Roslan Ismail^{3,4}, Nor Elliza Tajidin¹, Khairil Mahmud¹, and Siti Zaharah Sakimin¹

¹Department of Crop Science, Faculty of Agriculture, Universiti Putra Malaysia, 43400 UPM Serdang, Malaysia

²Faculty of Tropical Forestry, Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia

³Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, 43400 UPM Serdang, Malaysia

⁴Institut Tanah dan Ukur Negara (INSTUN), 35950 Tanjong Malim, Perak, Malaysia

ABSTRACT

Black soldier fly (*Hermetia illucens*) larvae frass has gained increasing attention as a potential biofertiliser due to its nutrient content and role in organic waste recycling. This study evaluated the effects of black soldier fly larvae (BSFL) frass on the growth of Pak Choy (*Brassica rapa* L.) and selected soil chemical properties under rain-shelter conditions. Five fertiliser treatments were arranged in a completely randomised design with six replicates: NPK fertiliser (15:15:15), single frass application (BF1), double frass application (BF2), combined NPK with single frass application (NBF1), and combined NPK with double frass application (NBF2). Plant growth was assessed using shoot and root fresh and dry weights, while soil pH, total nitrogen, and available phosphorus were measured after a 30-day growth period. Data were analysed using analysis of variance followed by least significant difference tests. Fertiliser treatments significantly influenced plant biomass,

soil pH, and available phosphorus, whereas soil total nitrogen did not differ significantly among treatments. The combined NPK and double frass treatment (NBF2) produced the highest shoot fresh weight, representing a 56.6% increase compared with NPK alone. Frass-only treatments resulted in biomass comparable to NPK fertiliser, indicating that BSFL frass was able to support Pak Choy growth under controlled conditions. Frass application also resulted in moderately higher soil pH, while available phosphorus declined in combined fertiliser treatments. Overall, BSFL frass shows potential as a supplementary organic fertiliser

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E-mail addresses:

gs63548@student.upm.edu.my (Soo Tsou Hung)

mboyiej@gmail.com (Mohamadu Boyie Jalloh)

elisa@upm.edu.my (Elisa Azura Azman)

roslanismai@upm.edu.my (Roslan Ismail)

elliza.tajidin@upm.edu.my (Nor Elliza Tajidin)

khairilmahmud@upm.edu.my (Khairil Mahmud)

szaharah@upm.edu.my (Siti Zaharah Sakimin)

* Corresponding author

for short-cycle leafy vegetables; however, field-scale validation and longer-term nutrient dynamics require further investigation.

Keywords: Black soldier fly farming, circular economy, organic waste composting, sustainable agriculture, waste to wealth

INTRODUCTION

In traditional agricultural practices for reducing agricultural waste, most farmers follow the decomposition procedures of burying waste back into the soil. This procedure can be called composting, as it reduces waste into nutrient-rich composts with the help of soil microbes or other decomposing agents. One of the most popular composting methods is through vermicomposting, with the help of earthworms (*Eisenia fetida*). This process of converting food waste to organic fertiliser through decomposers is one of the most practical cultures used in agriculture.

Another type of composting that has emerged in agriculture recently is BSFL compost. The larvae are from the black soldier fly (*Hermetia illucens*) (Diptera: Stratiomyidae), a decomposing agent alternative to traditional decomposition processes. Black Soldier Fly Larvae (BSFL) is one of the best insects for bioconversion processes. The larvae have an extremely voracious appetite and can consume a wide range of organic waste (Alattar et al., 2016), including food waste, crop straw (Gao et al., 2019) and animal manure (T. Liu et al., 2019; Z. Liu et al., 2018). The BSFL have received extensive attention due to their high levels of lipids and proteins.

The production of frass from BSFL also contributes much more to crop production improvements in yield and growth rates. Black Soldier Fly Larvae frass is rich in organic matter, which can help increase soil fertility and encourage microbial proliferation in soil (Zahn, 2017). Microorganisms break down organic matter to enrich the surrounding soil with nutrients the plants can use. With BSFL frass, fertiliser usage such as NPK fertiliser can be reduced (Schmitt & de Vries, 2020). Therefore, this helps to save costs and reduce the negative environmental impact.

Many research studies focus on pointing out the bioconversion performances of BSFL. However, few studies or articles have evaluated the effects of the BSFL frass in terms of nutrient values and the growth performance of plants. Synthetic fertilisers such as NPK fertiliser or organic fertilisers such as livestock waste products, can be utilised easily to improve soil quality and plant growth performance. However, there are some drawbacks to using these types of fertilisers. If synthetic fertiliser is used excessively, farmers will risk the excessive loss of nutrients when applying it to their crops (Sabry, 2015). Besides that, using livestock waste products as fertilisers could also potentially pose problems to crops when applied more than usual. For example, the high nitrogen content in the manure can cause nutrient toxicity to crops if not properly composted. Moreover, using BSFL frass as

a fertiliser is relatively new in the agriculture industry, and not many research institutes and universities focus particularly on this product. Therefore, this study was initiated to evaluate the fertilising performance of BSFL frass on the yield of Pak Choy and selected chemical properties in the soil compared with synthetic fertiliser NPK (15:15:15) application.

METHODOLOGY

Experimental Sites

The project was initiated and performed in three areas within the research field: the establishment of the Black Soldier Fly and production of frass inside the poultry facility (Figure 1), the establishment of Pak Choy plants was done for one planting season under the rain shelter, and the laboratory was used for ascertaining the plant growth performance and soil chemical properties.

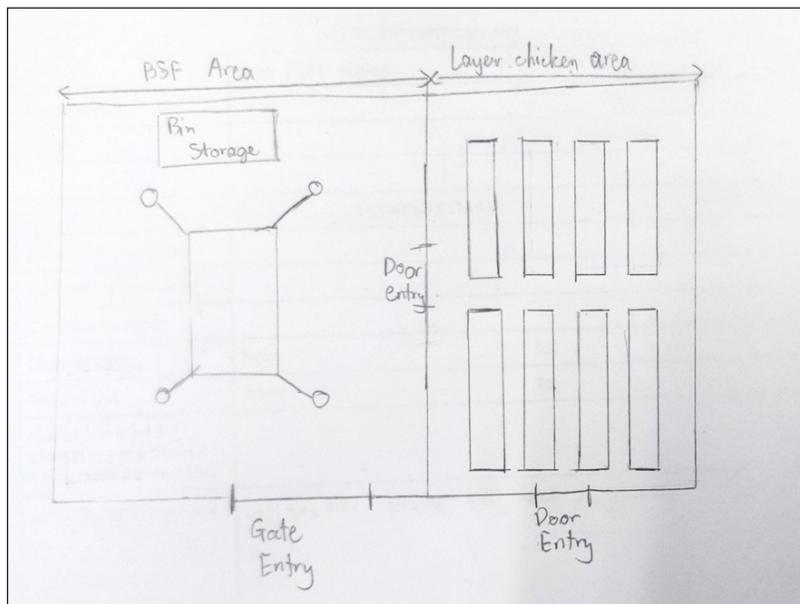


Figure 1. Illustration of BSFL establishment

Frass Production and Characterisation

The BSFL cage was built, and the adult flies were introduced into the cage. The modified egg trap for the flies to lay eggs was also constructed to collect and reproduce the larvae efficiently. There were also two plastic container boxes prepared for the larvae that functioned as the feed supplement area and the collection of frass, which was separated after the pupation stage of the flies and then transferred to another container and left to dry for a week in a dry and cool area to remove the moisture. The feeds supplied were food waste

from the cafeteria, fresh poultry manure, and crop waste (e.g., Kangkung). The rate of feed given was on a consistent organic feedstock mixture throughout the production period.

During the larvae stage, monitoring of the cage for prevention of infestation of other fly species laying eggs onto the feed besides adequate resupplying of feed, monitoring of escaped prepupae from the feed box and control of moisture and temperature by spraying mists of water into the cage were done daily, although moisture control was less required since the climate of Malaysia is hot and humid (Temperature range: 24-32°C; Relative humidity: 80-90%) (Orangutan Appeal UK, n.d), which provides optimal conditions for survivability and reproduction of larvae of BSF.

Fresh BSFL frass contained high initial moisture content typical of insect-derived residues. Prior to application, frass was air-dried under shaded, well-ventilated conditions for seven days until a stable, friable texture was obtained. The moisture content of the dried frass was approximately 25-30%, as estimated gravimetrically based on weight loss during the drying period. This drying step was conducted to reduce variability associated with excess moisture, improve handling consistency, and standardise application across treatments. All frass used in the experiment originated from a single production batch and was applied on a fresh weight basis.

Soil Preparation and Baseline Characterisation

Topsoil and Silabukan soils were collected from the university research farm, air-dried, and sieved through a 2-mm mesh to remove debris and ensure uniform particle size. The soils were thoroughly mixed in bulk prior to filling polybags to ensure homogeneity. Baseline soil chemical properties, including pH, total nitrogen, and available phosphorus, were analysed before treatment application and are presented in Table 2. Soil texture was determined using the Munsell Colour System and classified as sandy clay loam.

Planting and Crop Management

Curly Dwarf Pak Choy (*Brassica rapa* L.) seedlings were transplanted into polybags and grown for 30 days (FAO, 2024). All treatments received irrigation from the same water source at equal volumes throughout the experimental period to avoid differential nutrient inputs. Environmental conditions within the rain shelter, including temperature and relative humidity, were monitored regularly. Polybags were spaced 5cm apart to prevent nutrient cross-contamination through drainage.

Experimental Design and Treatments

Polybags (16" diameter × 16" height) were arranged on a uniform concrete surface to reduce spatial variability in soil moisture and nutrient movement. Based on this uniformity, a completely randomised design (CRD) was adopted. Five fertiliser treatments were

evaluated with six replicates per treatment. The treatments consist of NPK= NPK (15:15:15) fertiliser (NPK); BF1= one time BSFL Frass application (BF1); BF2= two times BSFL Frass application (BF2); NBF1= NPK (15:15:15) fertiliser + one time BSFL frass (NBF1); and NBF2= NPK (15:15:15) fertiliser + two time BSFL frass (NBF2). Frass application rates were selected based on ranges reported in previous BSFL frass studies and were intended to evaluate agronomically relevant responses rather than strict nutrient equivalence with NPK fertiliser, in addition of relevant information from Jabatan Pertanian Semanjung Malaysia (1998). The descriptions of each treatment are shown in Table 1.

Table 1
Description of the treatments used in the experiment

Treatment ID	Description	Rate (t ha ⁻¹)	Amount Per Polybag (g)
NPK (Control)	Conventional application of NPK (15:15:15) fertiliser	0.6	3
BF1 (Frass)	One Time (1x) BSFL Frass application	2.5	12.5
BF2 (Frass)	Two Times (2x) BSFL Frass application	5	25
NBF1 (NPK + Frass)	NPK (15:15:15) fertiliser + 1x BSFL frass	0.6 (NPK) + 2.5 (frass)	3 + 12.5
NBF2 (NPK + Frass)	NPK (15:15:15) fertiliser + 2x BSFL frass	0.6 (NPK) + 5 (frass)	3 + 25

*Source: Jabatan Pertanian Semanjung Malaysia (1998)

Frass Characterisation, Plant Growth, and Soil Analysis

Three types of parameters are measured in this experiment: (i) frass characterisation on total N and available P values, (ii) growth of Pak Choy, and (iii) selected soil chemical properties. Frass was collected after larval pupation, air-dried under shaded conditions for seven days to stabilise moisture content, and stored in sealed containers prior to application. All frass applied in the experiment originated from a single production batch to minimise variability in nutrient composition. Frass characterisation focussed on total nitrogen and available phosphorus, and potassium analysis was not conducted due to analytical constraints.

The parameters of plant growth measured are shoot fresh weight and dry weight, root fresh weight and dry weight and plant height. Plant height was measured every 10 days after the transplant. Fresh weight and dry weight of Pak Choy shoots and roots were measured with an electronic balance during 30 DAP, and the samples were transferred to the lab after being harvested. The results were recorded for dry weight after drying in the oven at 80 °C for 24 hours.

The soils were sampled before planting and during the harvesting of the Pak Choy. The soils were air-dried, ground with a mortar and pestle and sieved through a 2 mm sized

sieve. The ground samples were prepared for chemical analyses. Soil pH was analysed by two methods: (i) 1:2.5 (soil: distilled water) and (ii) 1:2.5 (soil: 0.01 M CaCl₂), then shaken with a rotary shaker at 180 rpm for 15 minutes, and then left for the suspension to settle for 1 day. Total nitrogen content was analysed by putting 2 g of soil in a CHN analyser. Soil available P was determined using the colourimetric method (Murphy & Riley, 1962). The P extraction solution was prepared by mixing 4.3 mL HCl and 0.7 mL H₂SO₄ in a 1 L volumetric flask and adding distilled water to the final volume; the reagent A was prepared by mixing 6 g ammonium molybdate and 74 mL H₂SO₄ solution in 500 mL and left cooled before added with 0.1454 g potassium antimony tartrate dissolved in 200 mL water, transferred to 1L volumetric flask and brought to volume with distilled water; and Reagent B was prepared by mixing 1.32 g of ascorbic acid with 250 mL reagent A. Calibration procedure was done by preparing potassium dihydrogen phosphate (KH₂PO₄) as P standard. A small amount of KH₂PO₄ was dried in an oven at 105 °C for 1 hour and left to cool in a desiccator before being prepared in 4.3935 g and mixed with distilled water in a 1 L volumetric flask at 1000 ppm concentration. Next, a 5 ppm KH₂PO₄ solution was prepared by diluting 5 mL of 1000 ppm KH₂PO₄ solution in another 1L volumetric flask. Finally, 5 different concentrations of solutions (0, 0.1, 0.2, 0.3, 0.4, and 0.5 ppm) in 50 mL volumetric flasks were prepared from a 5 ppm KH₂PO₄ solution and added with 8 mL reagent B before adding distilled water to the final volume. They were left for 15 minutes and read in a spectrophotometer at 882 nm for a standard curve. The extraction procedure was done by adding a 5 g soil sample and 20 mL extraction reagent in a plastic vial and shaking with 180 rpm in a rotary shaker for 10 minutes, then filtering in another vial to obtain supernatant. 2.5 mL supernatant was transferred to a 25 mL volumetric flask and mixed with 8 mL reagent B before adding distilled water to the final volume. The final solution was shaken and left for 15 minutes. The solution was read in a spectrophotometer at 882 nm for a standard curve, and the data was recorded.

Data Collection and Statistical Analysis

Plant height and shoot fresh weight were recorded at harvest. Soil samples were collected after harvest for analysis of pH, total nitrogen, and available phosphorus. Data were analysed using one-way analysis of variance (ANOVA). Normality and homogeneity of variance were verified using Shapiro-Wilk and Levene's tests, respectively. Mean separation was performed using the least significant difference (LSD) test following significant ANOVA results. Plants that were completely destroyed by pest damage were excluded from analysis using listwise deletion (< 5%), and degrees of freedom were adjusted accordingly. Statistical Analysis Software (SAS) version 9.4 was used to analyse the data collected.

RESULTS

Total N and Available P of Frass

Table 2 shows the nutrient content of BSFL Frass produced. Total nitrogen was 3.16%, and available phosphorus was 124 mg L⁻¹.

Table 2

Black soldier fly larvae frass nitrogen and phosphorus composition

Total Nitrogen (%)	Available Phosphorus (mg L ⁻¹)
3.16	124

Plant Growth

Shoot Fresh Weight and Dry Weight

Shoot fresh weight ($p = 0.020$) (Figure 2) and dry weight ($p = 0.045$) (Figure 3) of Pak Choy were significantly affected by fertiliser treatment. The combined application of NPK fertiliser with double-rate BSFL frass (NBF2) produced the highest shoot fresh weight among all treatments, at 19.44 g for shoot fresh weight and 1.69 g for shoot dry weight. Frass-only treatments (BF1 and BF2) did not differ significantly from the NPK-only treatment, indicating comparable biomass production under these treatments. Single-rate combined application (NBF1) resulted in intermediate shoot fresh weight values.

Root Fresh Weight and Dry Weight

The root samples also showed a similar trend as the shoot samples in both fresh weight ($p = 0.01$) (Figure 4) and dry weight ($p = 0.038$) (Figure 5). The data distribution's highest and lowest mean value was by NBF2 and BF2, at 1.024 g and 0.44 g for root fresh weight and 0.16 g and 0.088 g for root dry weight, respectively. Frass-only treatments resulted in comparable to NPK fertiliser, which shows there is no significance for interaction between NPK and all treatments.

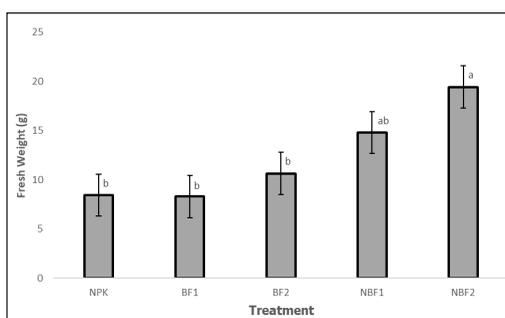


Figure 2. Effect of treatments on shoot fresh weight. Bars represent mean \pm standard error (SE)

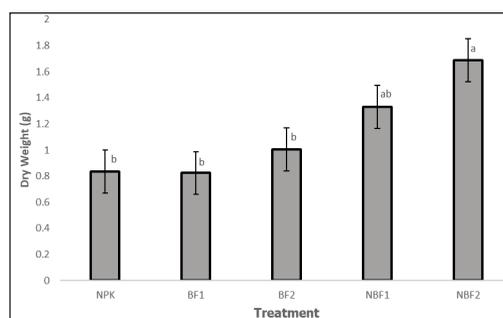


Figure 3. Effect of treatments on shoot dry weight. Bars represent mean \pm standard error (SE)

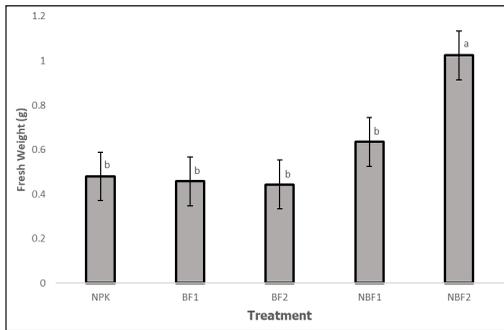


Figure 4. Effect of treatments on root fresh weight. Bars represent mean \pm standard error (SE)

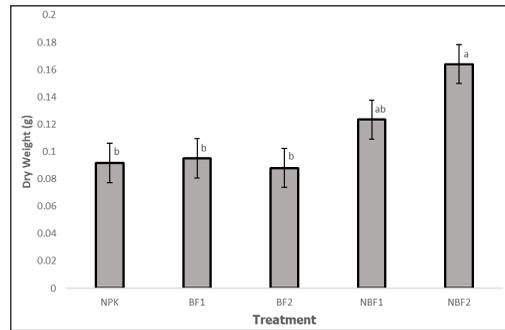


Figure 5. Effect of treatments on root dry weight. Bars represent mean \pm standard error (SE)

Plant Height

Plant height recorded throughout the growth stages (10, 20, 30 DAP) showed an increasing effect for treatments BF1, BF2, NBF1 and NBF2, compared to the decreasing trend from NPK treatment (Figure 6). In comparison, with the effects of 1 missing data value from BF2 and NBF2 each, they showed higher growth values than the other treatments in each treatment category (frass treatment and mixture treatment, respectively). Besides that, only BF2 displayed the highest value at 30 DAP at 9.04 cm with the effect of one missing value, while the lowest value at 30 DAP comes from NBF1, at 7.82 cm. Overall, the treatments BF1, BF2, NBF1 and NBF2 showed better growth results than the control treatments, and the doubled application rate of treatments BF2 and NBF2 showed an increase with a significant effect on plant height than BF1 and NBF1 treatments.

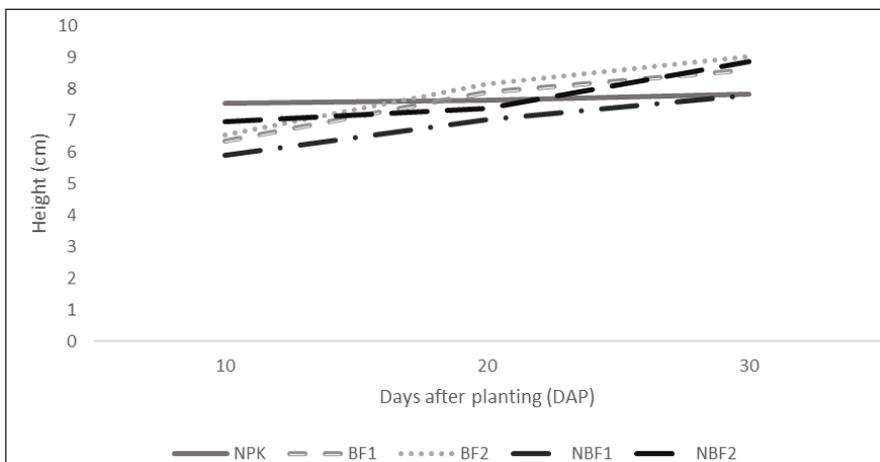


Figure 6. Effect of treatments on plant height

Pretreated Soil Chemical Properties

The recorded nutrient values of pretreated soil are shown in Table 3. pH values on water and the calcium chloride method were at 6.47 and 6.35, respectively. Total N content in soil was at 0.98%, and P available in soil was recorded at 1.88 mg L⁻¹.

Table 3

Nutrient values of pretreated soil

Soil parameter	Value
pH H ₂ O	6.47
pH CaCl ₂	6.35
Total N	0.98%
Available P	1.88 mg L ⁻¹

Soil pH

The pH readings showed that the soil from treatments BF1 to NBF2 was slightly alkaline at pH 8.00 for the H₂O method (Figure 7) and almost neutral (pH 7.00) for the CaCl₂ method (Figure 8), generally. Significant differences were shown in mean values among the four treatments in relation to the control NPK for both methods ($p < 0.0001$). Besides that, results from both methods also showed some similarities in comparison. Firstly, both results showed that the mean pH values from the control treatment NPK had the lowest values compared to the other four treatments. Secondly, the mixture of NPK fertiliser and BSFL frass from NBF2 showed the highest mean pH value among the treatments. However, the level of significance between BF1, BF2, NBF1 and NBF2 is very low, indicating pH of the soil level has little influence on these types of treatments.

There were some differences in the results shown by both methods. First, BF2 showed the second-highest mean value using the H₂O method, at 8.13. Meanwhile, NBF1 showed the second-highest mean pH value when measured by CaCl₂ at 7.23, while the second-lowest mean value was shown at 8.05 when measured by H₂O.

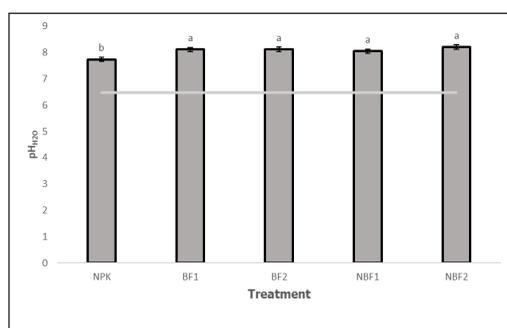


Figure 7. Effect of treatments on soil pH using the H₂O method. Bars represent mean \pm standard error (SE)

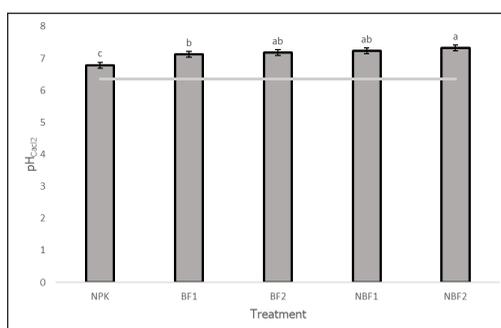


Figure 8. Effect of treatments on soil pH using the CaCl₂ method. Bars represent mean \pm standard error (SE)

Soil Total N and Available P

The mean values of total nitrogen content for the five different treatments were generally at approximately 1.00%, with the controlled treatment of frass fertiliser at BF1, while the mixture of NPK fertiliser and BSFL Frass (NBF2) resulted in very low mean values of 1.02% and 1.03%, respectively (Figure 9). The results showed no significant differences ($p = 0.566$) in total nitrogen content in the soil for the different treatments. Overall, doubled treatment of BSFL Frass at NBF1 showed the highest mean value of total N at 1.06%, and single treatment of BSFL Frass at BF1 showed the lowest total N content at 1.02%.

Phosphorus content available in soil generally decreases gradually from treatments NPK to NBF2 (Figure 10). There were significant differences in the data distribution among the 4 treatments in relation to the control treatment ($p < 0.0001$). Phosphorus available content from the control treatment NPK provided the highest mean value amongst the treatments at 11.06 mg L^{-1} . On the other hand, both frass treatments, BF1 and BF2, provided higher mean values than both mixtures of NPK fertiliser and frass treatments, NBF1 and NBF2, with BF1 being higher than BF2. In comparison, frass treatment BF1 showed a higher mean value than BF2, with a difference of 1.29 mg L^{-1} , while mixture treatment NBF2 showing higher value than NBF1, with a difference of 0.28 mg L^{-1} . The interaction within frass-only and mixed-fertiliser treatment groups shows no significance.

Additional Observations

There were some observations made during the growth stage of the Pak Choy as well. During the second week of the growth stage, the Pak Choy samples were growing variably for each treatment. Some samples were significantly larger in size, notably from treatments NBF1 and NBF2, which were the largest amongst all samples. Despite that, all samples from the five treatments showed growth during the growing period. Comparatively, treatments BF1 to NBF2 showed more significant growth in relation to the control treatment NPK in terms of growing size and plant damage scale that was caused by pest attacks and scorching.

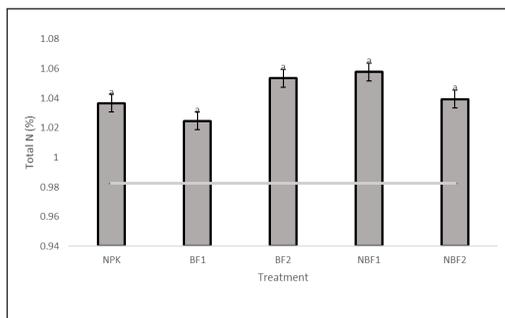


Figure 9. Effect of treatments on soil total nitrogen. Bars represent mean \pm standard error (SE)

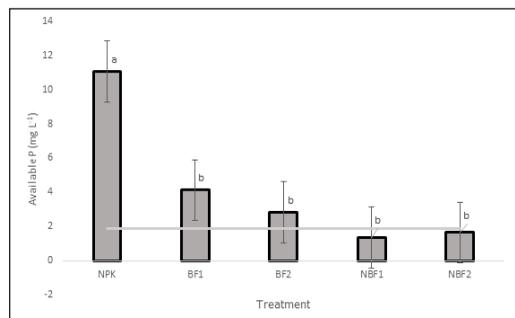


Figure 10. Effect of treatments on soil available phosphorus. Bars represent mean \pm standard error (SE)

There were visible types of pests inflicting damage. At the earlier stage, the Pak Choy samples were damaged variably from less to more by leafminers and Giant African snails (natively known as 'siput babi'), with Giant African snails appearing the most. With application of the homemade natural pest repellent and chitin obtained from carcasses of the adult BSF and pupa skin, the occurrence of leafminers was reduced to none the following week and the appearance of Giant African snails on the leaf surface of the samples. During the pest attack period, the samples from treatments BF1 to NBF2 had fewer pest attack occurrences compared to the control treatment NPK. From all 6 Pak Choy samples, 5 of the samples from Treatment 1 were damaged by pest attack, notably the worst from replicates 3 and 4, but were still intact with leaves remaining on the plants. Treatment 2 and 4 samples had less damage scale overall, with only partial damage caused by pests on BF1-R3 and NBF1-R4, while no visible damage was observed on the other samples. For treatment 3 and 5, 1 of 6 samples was damaged severely and was completely devoured by the pests, which explains the existence of missing data values for plant fresh weight, dry weight and final plant height, as well as damage intensity caused by the snails.

DISCUSSION

Frass Nutrient Properties

The nitrogen and phosphorus content of BSFL frass was shown to be a total N of 3.16% and an available P content of 124 mg L⁻¹. These nutrients provide a minimum supply for plant nutrient uptake to achieve positive growth. However, in reference to the article from Temple et al. (2013), the total N value of the frass was recorded at 4.54%, which is much different from the results shown, and no information on available phosphorus was found. The feasible explanation for these resulting values is that these products depend on the feeding value of the larvae, which is affected more by the protein content in the feed due to the larvae's requirement for protein to grow and enter the pupate stage for the metamorphosis process into adult flies.

Most insect substrates contain high soluble nitrogen content that can alter plant nutrient uptake, soil N availability, and influence growth positively, and BSFL frass is no exception. A study by Kagata and Oghushi (2012) stated that applying the insect N-rich frass on potted *B. rapa* samples resulted in a higher plant intake of inorganic N than that of insect-poor N frass. Besides that, the soil amendment performance of BSFL frass has proven similar to that of chicken manure. Therefore, it has been proven that BSFL frass has the potential for smallholders to replace livestock manure as a fertiliser treatment for crops since the frass can improve overall farm productivity (Quilliam et al., 2020).

Despite the comparison, various NPK values of frass from various production facilities in different countries exist. This can be due to the effects of the quality of feeding materials, some possible external factors such as temperature, humidity, and light intensity on the

reproduction rate of the adult flies, and management methods. Nevertheless, the nutrient values of the frass proved to be good for the fertilisation of crops, similar to the application of organic fertilisers in addition to the provision of inducing defensive mechanism triggers in the plants, whereby most of the organic fertilisers used by farmers do not contain such beneficial properties.

Besides that, BSFL frass was also observed to provide defensive properties for the plants to combat pest and pathogen attack, based on the additional observations made for treatments NPK to NBF2 that had included application of frass, which were observed to have a significant decrease in pest attack occurrence during the second week of growth stage. This is because the BSFL frass contains chitin, the component of insect cuticles that triggers the defensive response in the plants when applied, preventing the plants from being damaged by pest and disease attacks. Chitin content in the frass can be produced by harvesting a composting substrate from the BSF breeding area that contains moults of the larvae and the pupae cases (Quilliam et al., 2020). This provides more improvements in promoting plant growth without transmission of pathogens and pest attack with the BSFL frass (Choi & Hassanzadeh, 2019).

Plant Growth

Overall, Pak Choy's growth performance had an interesting outcome. Despite having lower NPK values of frass content and mixture content in the soil, the samples with frass and mixture fertiliser treatments showed more positive growth than the control treatment of NPK fertiliser application under controlled rainshelter conditions. NBF2 provided a better outcome due to the abundant nutrient supply for plant growth from the combination of frass and NPK fertiliser that increased the plant biomass of the Pak Choy. This may be due to the increase in N content in the leaf of Pak Choy in response to the increasing amount of frass, as soluble organic N from the application of frass was readily available for the plants (Kagata & Oghushi, 2012). Similar outcomes were also shown for the root fresh weight and dry weight of the Pak Choy samples, and explanations of the differences in the root fresh weight and dry weight.

Next, on plant height, the Pak Choy samples from BF2 had the highest values amongst the other samples, which provided a good assumption that the growth is affected positively more by the frass than the NPK fertiliser application. This means that BSF frass has the ability to provide more soluble N, P, and K in soil for plants' inorganic nutrient uptake to support growth compared to the NPK fertiliser. Comparatively, the mixture of frass and NPK fertiliser in treatments from NBF1 and NBF2 had a higher effect on the plant height than the frass treatments in BF1 and BF2 due to the combination of both fertilisers. Some studies agreed that frass can affect crops' growth more significantly than commercial synthetic fertilisers, such as NPK (15:15:15) fertiliser (Beesigamukama et al., 2020; Quilliam et al., 2020).

The results demonstrate that BSFL frass was able to support Pak Choy growth comparable to conventional NPK fertiliser under controlled rain-shelter conditions. Similar biomass production between frass-only and NPK treatments suggests that frass provided sufficient nutrients to sustain short-cycle leafy vegetable growth. The enhanced biomass observed under combined frass and NPK treatments indicates a complementary effect between organic and inorganic nutrient sources.

Soil Selected Chemical Properties

The pH values of the soil samples from treatments BF1 to NBF2 lean towards slightly more alkaline for the H₂O method and neutral for the CaCl₂ method, relative to the control treatment, which had slightly lower pH values, despite leaning towards neutral for both methods. The only feasible explanation for the occurrence is that BSFL frass has the ability to regulate soil pH to reach a neutral level, enabling more positive growth for the Pak Choy plants than the NPK fertiliser. The pH is one of the important factors influencing the provision of essential nutrients, which is the amount of essential nutrients available in the soluble soil. It also affects the root's ability for nutrient uptake. If the pH is too high (alkaline) or too low (acidic), there will be adverse effects on the nutrient absorption by the plants, and the soil will not be compatible for the plants to survive.

Nitrogen content in soil from treatments BF1 to NBF2 was shown to have more variability in total nitrogen content. For treatments BF1 and BF2, there is a notable increase in total nitrogen content with increasing application rates, which means that doubled application provided a better nitrogen supply for plant growth, including inorganic N absorption by roots. NBF1 was shown to have the highest total nitrogen content, which explains that the mixture provided the best nitrogen supply outcome for the soil in comparison with the other 4 treatments. Since there were no significant differences between the 5 treatments ($p > 0.05$), soil nitrogen supply is not generally affected by any fertiliser application, either NPK fertiliser, frass or a mixture of frass and NPK fertiliser. The pretreated soil total nitrogen (TN) value of 0.98% appears relatively high compared with mineral agricultural soils; however, this value reflects total nitrogen associated with a topsoil-based potting medium rather than plant-available nitrogen. The soil used in this study was collected from surface horizons enriched with organic matter, where nitrogen is predominantly present in organic forms bound within soil organic matter and microbial biomass. In pot experiments, soil is confined within a limited volume and is not subject to leaching losses, which can further concentrate organic nitrogen pools relative to field conditions. In addition, the reported TN value represents bulk nitrogen content and does not directly indicate nitrogen availability to plants, which depends on mineralisation dynamics rather than total concentration. The absence of significant differences in soil total nitrogen among treatments after harvest supports the interpretation that plant growth responses were

driven by nutrient availability dynamics and soil chemical conditions rather than initial bulk nitrogen levels.

Available phosphorus content in soil for treatments from BF1 and BF2 had higher values than NBF1 and NBF2. NBF1 and NBF2 recorded lower values due to the inclusion of frass that controls the P content in the soil, and the NPK fertiliser has a higher P_2O_5 value, which is at 15%. Despite such comparisons, the frass treatment was proven to have phosphorus content in the soil. Besides that, the recorded values of lower P content for BF1 to NBF2 compared to the control treatment NPK were shown to be irrelevant in comparison to studies by Temple et al. (2013) that displayed a positive response to an increase in soil P levels by increasing frass treatments for pak choy plants. The results could be correlated to the differences in soil status in comparison to this study, where in the field site from the research of Temple et al. (2013), the soil was classified as Humic Gleysol, which was clayey and had a high waterlogging status, while the soil from this study had high organic matter content due to topsoil included, therefore influencing the P content in the soil. Other explanations could be related to the influence of pH caused by frass input from BF1 and BF2, and mixture fertiliser input from NBF1 and NBF2 that altered the P content in the soil. With the regulation effect on pH in soil by the frass treatment and mixture treatment, the soil developed a nutrient supply for plants in high amounts, which has potential for the moderation of available P in soil. Since no other studies provided a sufficient and clear explanation of the soil P effects, both seemed most feasible concerning the results obtained.

Generally, the mixture of frass and NPK fertiliser was shown to perform better in nutrient availability in the soil than in the control and frass treatments. Despite such results, the frass treatment alone performed well regarding nitrogen and phosphorus availability in the soil due to its ability to regulate nutrient availability. The explanation above correlates with the discussion by researchers from Klammsteiner et al. (2020), Beesigamukama et al. (2020) and Temple et al. (2013).

Frass Application Rate Recommendations and Other Possible Mixture Combinations

The doubled application rate of treatment of frass from BF2 provided the most significant total nitrogen content compared to the single application rate of treatment of frass from BF1 based on the results combined, and therefore, theoretically, the crops should be applied frass at doubled rates to achieve better growth and yield. The combined fertiliser application also improved plant growth and yield outcomes, with increasing application rates providing better plant growth positivity. With reference to findings on plant growth performance by Beesigamukama et al. (2020), Zahn (2017) and Temple et al. (2013), it is accepted that increasing the application rate of BSFL frass can promote higher growth performance and yield.

The mixture treatment of frass and NPK fertiliser was also shown to have very positive results on soil nutrients and plant growth performance. Similar to the frass treatment group,

the doubled application rate of NBF2 showed better overall performance than NBF1 based on the overall results, which provides a concrete assumption that crops should be fertilised at twice the application rate for the mixture type. With the increasing application rate only from frass and the addition of inorganic fertiliser at a constant rate, both types of fertiliser tend to provide a higher improvement boost of soil nutrient supply and plant growth compared to solely frass application because of the addition of nutrient supply from the NPK fertiliser that plays a supporting role in the improvement of soil nutrient supply and plant growth while frass has the additional function of improving plant defence properties against invasion of pests and diseases.

However, for farmers who emphasise consideration of cost effectiveness and optimum frass application rates relative to income, application rates as low as 2.5 t ha⁻¹ could provide viable plant growth and yield for many farmers, especially for smallholders. The compilation of results above from pak choy yield value and soil nutrient aspects proved that 2.5 t ha⁻¹ of frass application rate offer similar outcome to NPK fertiliser application, considering the cost of buying NPK fertilisers and targeted nutrient improvement in soil that are the main concerns for many farmers. Therefore, frass can be utilised as an alternative to synthetic fertilisers due to its fertilisation value and accessibility.

Role of Microbial and Non-nutrient Effects

Microbial-mediated growth promotion and chitin-induced plant responses were not directly measured in this study. Although previous studies have reported such effects for insect frass, the present findings cannot distinguish nutrient effects from microbial or biochemical contributions. Therefore, these mechanisms are discussed as potential explanations supported by literature rather than experimentally verified outcomes.

Pest-related Observations

Reduced pest damage was observed in some frass-amended treatments; however, pest incidence was not quantified statistically and organic pest repellents were applied during the experiment. Consequently, pest-related observations are descriptive and should not be interpreted as causal effects of frass application.

Agronomic, Ecological, and Policy Context

From an agronomic perspective, the findings suggest that BSFL Frass can be used as an alternative nutrient source for leafy vegetable production under controlled conditions.

Research Limitations and Future Research

Although the overall results displayed positive feedback on the use of BSFL frass, the results are still lacking in terms of information on the usage rate and nutrient properties

of frass due to limitations, such as time constraints, unavailability of selected laboratory equipment and chemicals required for analysis of frass and soil, and lack of references to global research articles related to this field. This project was initiated based on recent information from recent journal articles, and there was no background information or any base studies regarding Black Soldier Fly at our university. Hence, the research findings were limited to pH, total N, and available P in frass and soil; plant growth, shoot and root dry weight, fresh weight, and plant height. Research constraints and lack of analytical resources are also the factors that prevented potassium dynamics, microbial properties, leaf nutrient concentrations, and biosafety parameters were not assessed.

There were also some unprecedented events and mistakes during the project period. The project was also done over a lengthy duration, which took approximately 8 months from the beginning to the end, as the frass obtained from the breeding area took 3 months to produce, and the planting process took 5 months due to some mistakes made, such as usage of soil for plants, invalidated planting pots for the planting process, and crops being damaged intensively by pests during the growing period. The first mistake was using soil, where Silabukan soil was applied first, without knowing that the soil texture was not suitable for the plants used in this project. The solution for the soil problem was to mix topsoil with silabukan soil at a ratio of 3:1, as recommended by my supervisor. The second problem was that the planting pots were not suitable, as the previous pots used were plastic bottles, which could cause problems with the overall root and shoot growth of Pak Choy samples, resulting in the use of polybags as a solution. The last mistake was not caring for the plant samples well enough, resulting in damage to leaves caused by pests and pathogens. The replanting process was done two times: the first time planting on a soil mixture and without the application of homemade natural pest repellent and application of chitin, and the second time with over-application of pest repellent, letting the plants be exposed to the sun, which caused scorching damage to the plants. These discrepancies must be addressed to obtain more accurate results and provide reliable outcomes by other researchers. Future studies should incorporate multi-cycle field trials, comprehensive nutrient profiling, microbial analyses, and economic evaluation to better assess the fertiliser substitution potential of BSFL frass.

CONCLUSION

This study demonstrated that BSFL frass influenced Pak Choy growth and selected soil chemical properties under rainshelter conditions. Mixed NPK fertiliser and BSFL frass treatment (NBF2) resulted in the highest plant biomass, while frass-only treatments produced growth responses comparable to conventional NPK fertiliser. These results indicate that BSFL frass can contribute to nutrient supply for short-cycle leafy vegetables without hindering plant growth.

Soil pH was moderately increased following frass application, whereas no significant difference among treatments was found in soil total nitrogen, suggesting that growth responses may be influenced by factors beyond bulk soil nutrient concentrations. Changes in available phosphorus highlight the complexity of nutrient interactions when organic and inorganic fertilisers are combined.

Although BSFL frass shows potential as a supplementary organic fertiliser, conclusions regarding fertiliser substitution, pest suppression, and nutrient regulation should be interpreted cautiously due to the pot-based experimental design, single cropping cycle, and limited soil chemical measurements. Further research incorporating field trials, multiple cropping cycles, and comprehensive nutrient and microbial analyses is necessary before broader agronomic recommendations can be made.

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