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*Research article*

# Evaluating Black Soldier Fly (*Hermetia illucens* (L.) Residues from Various Organic Feedstocks as Organic Fertilizers for Sweet Corn Cultivation in Thailand

**Supphawed Tussanakit[1], Sirinapa Chungopast[1]* Chanwit Kaewtapee[2], Roungthip Masmeatathip[3], Yoshiki Matsumoto[4], Kiyonori Kawasaki[4] and Mika Nomura[4]**

*[1]Department of Soil Science, Faculty of Agriculture at Kamphaeng Saen, Kasetsart University, Kamphaeng Saen campus, Nakhon Pathom 73140, Thailand*
*[2]Department of Animal Science, Faculty of Agriculture, Kasetsart University, Bangkok 10900, Thailand*
*[3]Department of Entomology, Faculty of Agriculture at Kamphaeng Saen, Kasetsart University, Kamphaeng Saen campus, Nakhon Pathom 73140, Thailand*
*[4]Faculty of Agriculture, Kagawa University, Miki-cho, Kita-gun, Kagawa 761-0795, Japan*

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## Abstract

Black soldier fly (BSF, *Hermetia illucens* (L.)) cultivation produces residues that can serve as valuable sources of organic matter. In this study, we used five organic materials—chicken feed, tofu meal, pineapple peel, cassava meal, and dry chicken manure—as feed for BSF larvae. The nutrient content and properties of the resulting residues for sweet corn cultivation were analyzed. The highest decomposition rate was observed with tofu meal, at 46.46 mg $day^{-1}$. Residues from BSF larvae fed chicken feed were the richest in nitrogen at 3.75%. Residues from larvae fed dry chicken manure and pineapple peel contained the highest levels of phosphorus and potassium at 4.88% and 5.17%, respectively. All treatments, except for those with dry chicken manure, showed extremely high levels of organic matter in the range of 32.56–83.52%. Notably, residues from BSF larvae fed cassava meal exhibited the highest seed germination index at 94.87% as well as the highest unhusked ear weight, at 437.10 kg $ha^{-1}$ and husked ear length, at 18.47 cm. These results showed that the use of BSF residues improved the growth and yield of sweet corn. Thus, these findings suggest the potential for using BSF-derived organic fertilizers in sweet corn cultivation in Thailand.

**Keywords:** black soldier fly, decomposition, organic material, sweet corn, organic fertilizer

*Corresponding author: E-mail: agrsrnp@ku.ac.th
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## 1. Introduction

*Hermetia illucens* (L.), commonly known as the black soldier fly (BSF), belongs to the order Diptera. This insect is not considered a plant disease vector and is native to temperate and tropical regions. It is widely used for waste management purposes (Wang & Shelomi, 2017). BSF prefers shaded areas under trees and acts as a scavenger, decomposing organic matter (Kim et al., 2010; Ewusie et al., 2019). BSF larvae thrive among in various decomposing materials, such as fruits, animal remains, and manure, and can reduce manure accumulation by more than 50% (Tomberlin & Sheppard, 2001). Mass production of BSF for rearing purposes generates large quantities of residues. The amounts of residue produced from rearing with one ton of chicken manure, cow manure, mill by-products, and fruits and vegetables were 244 kg, 512–656 kg, 436 kg, and 400 kg dry matter (DM), respectively (Lopes et al., 2022). BSF residues, often referred to as 'frass,' are rich in organic matter and contain essential plant nutrients, including nitrogen, phosphorus, and potassium (Borkent & Hodge, 2021). Residues from BSF raised on household organic waste were found to contain high nitrogen content in the form of ammonium, positively influencing the growth of *Brassica rapa* var. *perviridis* (Kawasaki et al., 2020). Similarly, the application of BSF frass to Pakchoi (*Brassica rapa* L.) was shown to improve plant growth (Agustiyani et al., 2021). In summary, BSF effectively manages large volumes of waste, and its residues can serve as valuable organic fertilizers in agriculture.

Soaring natural gas prices, especially in Europe, have led to a broad reduction in ammonia production, which is an important component of nitrogen fertilizers. Similarly, soaring coal prices in China have affected its use as fuel to produce high-quality urea fertilizer, prices of which went up by 220% between April 2020 and March 2022 and were the highest for 23 months since 2008 (World Bank Group, 2022). Likewise, fertilizer prices in Thailand have been highly volatile due to global market trends and supply chain issues, with significant increases in 2023, during which nitrogen, phosphate, and potassium-based fertilizers reached THB 30,000–35,000 ton$^{-1}$, THB 38,000 ton$^{-1}$, and THB 32,000 ton$^{-1}$, respectively (The Nation, 2022). Annual demand for chemical fertilizers ranged from 5.0 to 6.0 million tons during 2016–2021, with urea (46-0-0) accounting for the largest share at 42% (Tunpaiboon, 2023). Subsequently, the proposed use of BSF residues as organic fertilizers in combination with chemical fertilizers due to current crop production is affected by the high cost of chemical fertilizer production.

Application of organic fertilizer along with the reduced use of chemical fertilizer is available as an alternative method of cultivation for farmers. Chemical fertilizers can deliver high nutrient content to plants in a soluble and immediately available form, while organic fertilizers offer a more balanced nutrient supply that helps to maintain the health of plants, enhances root growth, releases nutrients slowly, and promotes high organic matter in the soil (Chen, 2006; Sharma & Chetani, 2017). Farmers have largely cultivated the BSF with a focus on using it as a source of protein for animal feed. However, in the process of cultivating the larvae, a large amount of residual content that still retains a significant amount of available nutrients is produced. For example, the residues of BSF larvae fed with fruit and vegetable wastes were found to contain nitrogen concentrations up to 18.3 g kg$^{-1}$, while those fed with chicken feed contained 25.9 g kg$^{-1}$. Additionally, residues from larvae fed with biodegradable wastes contained other nutrients, including calcium, magnesium, sodium, iron, copper, manganese, and zinc (Klammsteiner et al., 2020; Lopes et al., 2022). It is therefore possible to use the residues obtained from BSF rearing as organic fertilizer to grow economic crops and to promote the concept of zero waste as part of the bio-circular-green economic model.

The aim of this research was to investigate the composition and efficacy of residues derived from BSF larvae fed with five organic materials on the growth and yield of sweet corn, and to compare those residues with the organic fertilizer standards of Thailand.

## 2. Materials and Methods

### 2.1 Black soldier fly larval culture

A completely randomized design was prepared with 6 treatments and 3 replications. The process of raising black soldier fly (BSF) larvae was conducted after approval for animal care and use for scientific research from Kasetsart University (ID: ACKU67-AGK-020). The BSF larvae were fed with various organic materials, namely chicken feed, tofu meal, pineapple peel, cassava meal and dry chicken manure, in plastic trays with the size 39 × 50 × 10 cm. Each plastic tray was filled with 150 g of coconut coir as bedding for the habitat of the BSF larvae. Then, the BSF larvae were counted and placed with 500 larvae per tray, and each type of organic material was added for feeding every 3 days. The larvae were raised at a controlled temperature of 30 °C and a moisture content of 70% (modified from Sheppard et al., 2002; Makkar et al., 2014). A 200 g sample of each of the residues was randomly collected for further analysis.

### 2.2 Determination of chemical composition and decomposition rate of the organic materials

Proximal compositions (protein, crude fat, crude fiber and ash) of the organic materials were analyzed according to AOAC (Helrich, 1990). The determination of the decomposition rates of the organic materials was performed by analyzing the weight before and after by using the formula for the exponential decay model (Olson, 1963): In (Xt/X0) = -kt, where Xt = the residual weight of decomposition at time t (g), X0 = dry weight of the initial fraction, k = the decomposition rate, and t = the study period. The dry weight of the organic material samples and bedding was measured both before and after raising the BSF larvae for 23, 23, 26, 26 and 44 days on chicken feed, tofu meal, pineapple peel, cassava meal and dry chicken manure, respectively. Materials were dried in an oven at 100 °C for 1 day and then placed in a desiccant chamber.

### 2.3 Soil and residues from the black soldier fly analysis

Soil samples were collected at approximately 20 points in the area of 14.035016°N, 99.956762°E, Thung Bua Subdistrict, Kamphaeng Saen District, Nakhon Pathom Province, at a depth of 0–30 cm. The potential of hydrogen (pH) and electrical conductivity (EC) were analyzed using a pH and an EC meter, respectively. Organic matter (Walkley & Black, 1934), available phosphorus (Bray & Kurtz, 1945), exchangeable potassium, calcium and magnesium were other soil properties evaluated (Pratt, 1965). A portion of the residues in the BSF larvae cultivation system was analyzed after the residues were kept in the shade until dry. Analysis was conducted in accordance with the organic fertilizer standards of Thailand for pH, EC, organic matter, organic carbon, carbon to nitrogen ratio, moisture, germination index, total nitrogen, total phosphorus, total potassium, particle size of organic fertilizer, and the presence of stone, gravel, plastic, glass or sharp material content (Department of Agriculture, 2008; 2012).

### 2.4 Sweet corn cultivation

The effect of the BSF residues on the growth and yield of sweet corn in pots under the greenhouse conditions was investigated. The soil was mixed and then put into 17-inch pots. Corn (*Zea mays* L.) was planted by sowing 3 seeds in each pot. When the corn seedlings were 14 days old, two of them were removed and the remaining one was allowed to continue growing (one plant per each pot). The soil was analyzed prior to the planting to determine the rate of fertilizer according to the Department of Agriculture (2012). The combinations of 75% chemical fertilizers and 25% being each of the various BSF residues were applied to the sweet corn in order to reduce the use of chemical fertilizers, and the plants were watered every 2–3 days.

The completely randomized design was planned with 3 replications and 6 treatments consisting of T1: 75% chemical fertilizer (CF) based on the soil analysis, T2: 75% CF + 25% residue from BSF raised on chicken feed, T3: 75% CF + 25% residue from BSF raised on tofu meal, T4: 75% CF + 25% residue from BSF raised on pineapple peel, T5: 75% CF + 25% residue from BSF raised on cassava peel, and T6: 75% CF + 25% residue from BSF raised on dry chicken manure. Growth analysis of the sweet corn was conducted for height and stem diameter. For the yield of sweet corn, ear number, unhusked ear diameter, unhusked ear weight, husked ear length, husked ear diameter, husked ear weight, fresh plant weight and fresh root weight were analyzed. All data were collected at 2, 4, 6, and 8 weeks after planting. The data were then analyzed using statistical analysis of variance, by comparison of means and Duncan's new multiple range test (DMRT) at a 0.05% confidence level ($P \leq 0.05$).

## 3. Results and Discussion

### 3.1 Proximal composition and decomposition rate of organic materials

From the results of the proximal composition analysis (Table 1), it was found that tofu meal (26.93%), chicken feed (21.66%) and dry chicken manure (19.96%) had higher protein content than the pineapple peel and cassava meal. Chicken feed had the highest crude fat content (7.97%) while the crude fiber content was the lowest (2.00%). Pineapple peel and cassava meal were high in crude fibers at 19.85 and 17.09%, respectively. However, the greatest amount of ash was found in dry chicken manure (38.10%). From the experimental results, it was found that the use of tofu meal to feed the BSF larvae (Figure 1a) resulted in the highest decomposition rate, at 46.46 mg $day^{-1}$, followed by the decomposition rates of chicken feed, pineapple peel, cassava meal and dry chicken manure of 26.13, 19.27, 19.55 and 8.44 mg $day^{-1}$, respectively. The different colors and characteristics of the residues from the BSF rearing are displayed in Figure 1b.

The BSF insects can decompose a wide variety of organic waste. Raising the BSF larvae with various organic materials resulted in the different decomposition rates. The highest decomposition rate of the tofu meal indicated that the BSF preferred tofu to the other organic materials and therefore took less time to consume it. The fresh weight composition of the tofu meal and chicken contained the highest protein and lipid contents, respectively, which the BSF larvae need for their growth. The nutrients in the feed, including proteins and lipids, are digested and utilized for accumulation of insect biomass (Zheng et al., 2012), and the composition of the biomass depends on feed intake and grain diet (Gobbi et al., 2013; Nguyen et al., 2015). The lower nutritional value of dry chicken manure explains why the larvae preferred it less and its decomposition rate was the lowest.

Pineapple waste contained significantly high average crude fiber content at 39.75% (Idayanti et al., 2022). Furthermore, it was reported that cassava meal contained neutral detergent fiber (NDF) and acid detergent fiber (ADF) at 8.0 and 5.4%, respectively (Lukuyu et al., 2014). These high fiber contents of cassava meal may explain its low rate of decomposition by the larvae.

**Table 1.** Proximal composition of each organic materials used in this study

| Organic Materials | Protein (%) | Crude Fat (%) | Crude Fiber (%) | Ash (%) |
|---|---|---|---|---|
| Chicken feed | 21.66±0.12$^{ab}$ | 7.97±0.57$^{a}$ | 2.00±0.01$^{e}$ | 7.59±0.16$^{c}$ |
| Tofu meal | 26.93±5.31$^{a}$ | 3.83±0.38$^{b}$ | 12.18±0.33$^{d}$ | 4.22±0.04$^{d}$ |
| Pineapple peel | 8.54±0.05$^{c}$ | 0.59±0.12$^{c}$ | 19.85±0.20$^{a}$ | 8.70±0.02$^{b}$ |
| Cassava meal | 10.89±0.02$^{c}$ | 0.08±0.02$^{c}$ | 17.09±0.03$^{b}$ | 8.69±0.08$^{b}$ |
| Dry chicken manure | 19.96±0.37$^{b}$ | 0.74±0.08$^{c}$ | 13.89±0.51$^{c}$ | 38.10±0.16$^{a}$ |
| F -test | ** | ** | ** | ** |

Significant differences of the various organic materials are indicated with different letter, ** P < 0.01

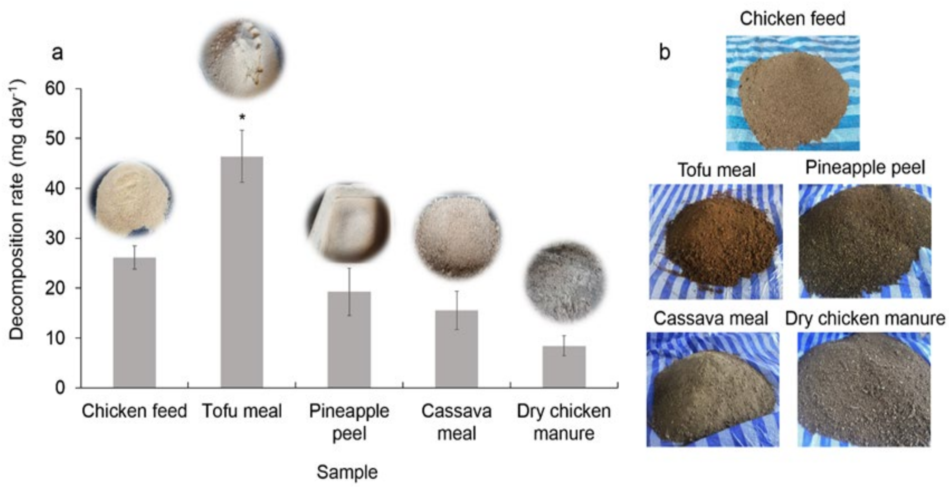


**Figure 1.** Decomposition rates of various organic materials (a) and different residues from the black soldier fly rearing (b) are shown. Statistically significant differences of organic materials are indicated with * (P < 0.05). The error bar shows standard deviation.

### 3.2 Physiochemical properties of soil and residues from black soldier fly cultivation

In this study, the soil of Thung Bua Subdistrict, Kamphaeng Saen District, Nakhon Pathom Province was used because it is an area where corn is grown. The soil texture is characterized as sandy loam soil with a slightly acidic pH (6.12) and $EC_e$ of 2.80 dS m$^{-1}$. The percentage of organic matter (0.75%) was low. Available phosphorus (86.35 mg kg$^{-1}$)

was remarkably high. Exchangeable potassium, calcium and magnesium were 83.63, 197.31 and 167.60 mg kg$^{-1}$, respectively. The fertilizer rate of nutrient content N-$P_2O_5$-$K_2O$ (187.5-0-31.25 kg ha$^{-1}$) was determined based on soil analysis and was applied with a ratio of only 75% in order to reduce the use of chemical fertilizer.

Analysis of the residues obtained from raising BSF larvae in order to assess their potential as organic fertilizers for promoting the growth of sweet corn (Table 2) showed that the residues from the various organic materials had different properties. The pH of residues from the BSF raised using pineapple peel (8.97) and dry chicken manure (9.20) was alkaline, while that using chicken feed (4.98) was acidic. The pH of all residues ranged from 4.98–9.20. The EC of the residues was in a range of 4.80–8.61 dS m$^{-1}$. The residues from the BSF raised using chicken feed were found to have the highest EC (8.16 dS m$^{-1}$), while that from the cassava meal was the lowest (4.8 dS m$^{-1}$). The sodium content of the residues was in a range of 0.05–0.37%. The sodium content of the residues from BSF raised using dry chicken manure and chicken feed were 0.36 and 0.37%, respectively. Organic matter of the residues was in a range of 32.56–83.52%, and organic carbon was in a range of 18.89–48.44%. Residues from the BSF raised using chicken feed had the highest organic matter and organic carbon content, which were 83.52 and 48.44%, respectively. The carbon to nitrogen ratio of residues among tofu meal, pineapple peel, and cassava meal were higher compared to those of chicken feed and dry chicken manure. Residues from the BSF raised using cassava meal had the highest germination index at 94.87%. The moisture of the residues was in the range of 3.12–16.80%, and high moisture contents were found in the pineapple peel larvae and tofu meal larvae residues at 16.80 and 10.48%, respectively. The nitrogen, phosphorus and potassium contents of the residues were in a range of 0.83–3.75, 0.14–4.88 and 0.65–5.17%, respectively. The highest nitrogen content of residues from the BSF raised using chicken feed was 3.75%. The highest phosphorus content of the residues was from the BSF raised using dry chicken manure (4.88%), while the residues from the BSF raised using pineapple peel and tofu meal had the highest potassium contents of 5.17 and 4.04%, respectively.

The residues obtained from raising BSF can be used as organic fertilizers, as they contain nutrients that are beneficial for soil amendment and plant growth. Relatedly, the nitrogen and phosphorus in recycled agro-industrial waste were retained in BSF frass (Beesigamukama et al., 2021), and the residues were successfully used as a fertilizer substitute for crops such as baby leaf lettuce, basil, and tomato (Setti et al., 2019). Residues from BSF larvae fed with chicken feed had the highest nitrogen concentrations, while those fed with dry chicken manure and pineapple peel showed the highest phosphorus and potassium contents, the levels of which were consistent with the nutrient compositions of the feed materials (Materechera & Morutse, 2009; Rajasekhar et al., 2020; Kacprzak et al., 2023; Mehraj et al., 2024). All residues had high levels of organic matter and could improve soil nourishment. The advantages of using organic fertilizers are that they reduce costs and improve soil structure, texture and aeration. Moreover, they increase the ability to retain water in the soil and stimulate root development (Assefa & Tadesse, 2019). The amount of sodium salts in the residues was not high enough to interfere with plant growth. Bazihizina et al. (2012) reported that salinity affected the physiological responses of plants in the shoots and roots and also affected water absorption. Soil pH between 5.8 and 6.2 is considered optimal for sweet corn production (Sullivan et al., 2020). In the current research, the starting soil pH was 6.12. As a result, the application of the residue from the BSF fed with casava meal (pH = 5.50) can be used to adjust the pH to the appropriate range for growing sweet corn. This residue also offers a high germination index, indicating that it is suitable for seed germination, which is used as an indicator of compost maturity (Yang et al., 2021).

**Table 2.** The properties of residues from black solider fly larval culture using various organic materials

| Properties | Chicken Feed | Tofu Meal | Pineapple Peel | Cassava Meal | Dry Chicken Manure | F - test |
|---|---|---|---|---|---|---|
| pH (1:5) | 4.98 ± 0.04$^{d}$ | 8.18 ± 0.04$^{b}$ | 8.97 ± 0.01$^{a}$ | 5.5 ± 0.25$^{c}$ | 9.2 ± 0.07$^{a}$ | * |
| EC 1:10 (dS/m) | 8.61 ± 0.67$^{a}$ | 6.99 ± 0.35$^{b}$ | 7.35 ± 0.35$^{b}$ | 4.8 ± 0.03$^{c}$ | 6.71 ± 0.05$^{b}$ | * |
| OM (%) | 83.52 ± 0.32$^{a}$ | 81.39 ± 2.01$^{ab}$ | 81.8 ± 1.42$^{ab}$ | 79.99 ± 0.77$^{b}$ | 32.56 ± 0.00$^{c}$ | * |
| OC (%) | 48.44 ± 0.14$^{a}$ | 47.2 ± 0.21$^{c}$ | 47.45 ± 0.19$^{b}$ | 46.39 ± 0.07$^{d}$ | 18.89 ± 0.17$^{e}$ | * |
| C:N ratio | 12.92 ± 0.07$^{d}$ | 33.24 ± 0.03$^{c}$ | 40.56 ± 0.03$^{b}$ | 55.89 ± 0.08$^{a}$ | 11.05 ± 0.02$^{e}$ | * |
| Moisture content (%) | 3.12 ± 0.25$^{e}$ | 10.48 ± 0.12$^{b}$ | 16.8 ± 0.17$^{a}$ | 3.79 ± 0.15$^{d}$ | 4.38 ± 0.07$^{c}$ | * |
| Germination index (%) | 1.53 ± 0.07$^{e}$ | 39.74 ± 0.05$^{d}$ | 44.65 ± 0.01$^{b}$ | 94.87 ± 0.04$^{a}$ | 43.99 ± 0.09$^{c}$ | * |
| Total N (%) | 3.75 ± 0.02$^{a}$ | 1.42 ± 0.03$^{c}$ | 1.17 ± 0.00$^{d}$ | 0.83 ± 0.04$^{e}$ | 1.71 ± 0.01$^{b}$ | * |
| Total $P_2O_5$ (%) | 1.31 ± 0.00$^{b}$ | 0.62 ± 0.01$^{c}$ | 0.58 ± 0.02$^{c}$ | 0.14 ± 0.01$^{d}$ | 4.88 ± 0.13$^{a}$ | * |
| Total $K_2O$ (%) | 1.77 ± 0.04$^{d}$ | 4.04 ± 0.20$^{b}$ | 5.17 ± 0.38$^{a}$ | 0.65 ± 0.04$^{e}$ | 2.89 ± 0.22$^{c}$ | * |
| Na (%) | 0.36 ± 0.00$^{a}$ | 0.12 ± 0.00$^{c}$ | 0.05 ± 0.01$^{d}$ | 0.3 ± 0.04$^{b}$ | 0.37 ± 0.02$^{a}$ | * |

Values are the mean±standard deviations (n = 3). Significant differences of various organic materials are indicated with different letters, * $P < 0.05$.

### 3.3 Quality of the residues obtained from black soldier fly cultivation compared to the organic fertilizer standards of Thailand

Residues obtained from the raising of BSF using different kinds of organic materials were compared with the Thai organic fertilizer standards in order to assess the feasibility of developing the BSF residues into commercial organic fertilizers (Table 3). It was found that the residue size did not exceed the specified standards and that there was no contamination from rocks, gravel, plastic, glass, sharp materials, or metals. Moreover, all residues met the organic fertilizer standards for EC, sodium content, moisture, organic matter, organic carbon, and total potassium. Residues from BSF raised using tofu and cassava meal also met the pH standards. Residues using chicken feed and dry chicken manure met the carbon to nitrogen ratio standard, and the residues that met the nutrient content criteria were those from chicken feed, tofu meal, pineapple peel and dry chicken manure. Although none of the residues obtained from the BSF rearing satisfied all of the criteria for commercial organic fertilizers in Thailand, all of them can still be used as organic fertilizers.

The residues from BSF can enhance soil health, promote healthy plant growth, reduce the need for chemical fertilizers, and prevent rapid nutrient leaching (Manan et al., 2024). In the current research, there is a tendency for the residues to meet the standards through improvements in quality by a process of being composted with other organic materials before use in order to ensure complete decomposition. Mature compost was shown to release beneficial nutrients to plants via a mineralization process (Al-Bataina et al., 2016). Alternatively, these residues can be used in combination with chemical fertilizers at an appropriate rate so as to reduce the amount of chemical fertilizers needed and to enhance their efficiency. The use of organic fertilizers in combination with chemical fertilizers has been shown to promote soil structure, soil microbial communities, and sweet corn growth (Lazcano et al., 2013; Canatoy & Daquiado, 2021).

### 3.4 Growth and yield of sweet corn with residue from black soldier fly combined with chemical fertilizer

The growth and yield of sweet corn were investigated based on the application of soil analysis when 75% chemical fertilizers and 25% different residues from the BSF raising were supplied to reduce the use of chemical fertilizers. The results are presented in Figure 2. No statistically significant differences in plant height were found at 2, 6, and 8 weeks (Figure 2a). The highest plant height was 27.4 cm when tofu meal residue was applied at 4 weeks. The maximum plant height was reached at 8 weeks ranging from 108–131.5 cm. Stem diameter was not different at 2 and 6 weeks (Figure 2b). Applied residue resulting from tofu meal, dry chicken manure and chicken feed resulted in significantly higher stem diameter compared to the use of only 75% chemical fertilizers, and were 1.99, 1.94 and 1.88 cm at 4 weeks, respectively. At 8 weeks, the range of stem diameters was 2.05–2.74 cm, and the highest stem diameter was 2.74 cm when residue based on tofu meal was applied. Figure 3a shows the yield of sweet corn. Ear number (1.33–2.00 ear plant$^{-1}$), unhusked ear diameter (3.86–5.07 cm), and husked ear diameter (3.24–4.28 cm) showed no differences between treatments. The highest fresh plant weight was 355.56 g when residue based on tofu meal was applied. It was noteworthy that the applied residue from cassava meal produced the highest unhusked ear weight, husked ear length, husked ear weight and fresh root weight at 437.10 kg ha$^{-1}$, 18.47 cm, 247.36 kg ha$^{-1}$ and 163.15 g, respectively. The husked ears were large and full of seeds with the application of the residue from cassava meal (Figure 3b, T5). Moreover, the roots had very high biomass and were strongly branched (Figure 3c, T5).

**Table 3.** Residue quality according to the organic fertilizer standards of Thailand from black solider fly larval culture using various organic materials.

| **Properties** | **Standard** | **Chicken Feed** | **Tofu Meal** | **Pineapple Peel** | **Cassava Meal** | **Dry Chicken Manure** |
|---|---|---|---|---|---|---|
| pH (1:5) | 5.5 – 8.5 | np | p | np | p | np |
| EC 1:10 (dS $m^{-1}$) | Not more than 10 dS/m | p | p | p | p | p |
| OM (%) | Not less than 20% by weight | p | p | p | p | p |
| OC (%) | - | p | p | p | p | p |
| C:N ratio | Not more than 20: 1 | p | np | np | np | p |
| Moisture content (%) | Not more than 30% of weight | p | p | p | p | p |
| Germination Index (%) | Not less than 80% | np | np | np | p | np |
| Total N (%) | Not less than 1.0% of weight | p | p | p | np | p |
| Total $P_2O_5$ (%) | Not less than 0.5% of weight | p | p | p | np | p |
| Total $K_2O$ (%) | Not less than 0.5% of weight | p | p | p | p | p |
| Total macronutrients (%) | Not less than 2.0% by weight | p | p | p | np | p |
| Na (%) | Not more than 1% by weight | p | p | p | p | p |
| Size (mm) | Not more than 12.5x12.5 mm | p | p | p | p | p |
| Gravel (%) | Not more than 2% of weight | p | p | p | p | p |
| Plastic, glass and etc. (%) | Must not be found | p | p | p | p | p |
| Organic fertilizer quality | | np | np | np | np | np |

Passed (p) and did not pass (np)

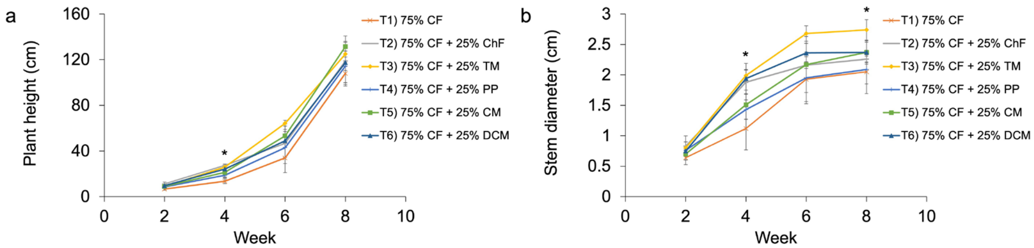


**Figure 2.** Plant height (a) and stem diameter (b) of sweet corn with application of chemical fertilizers according to soil analysis (CF) and in combination with different residues from the black solider fly (BSF) raised using chicken feed (ChF), tofu meal (TM), pineapple peel (PP), cassava meal (CM) and dry chicken manure (DCM) at 2–8 weeks. Statistically significant differences are indicated with * (P < 0.05). The error bar shows standard deviation.

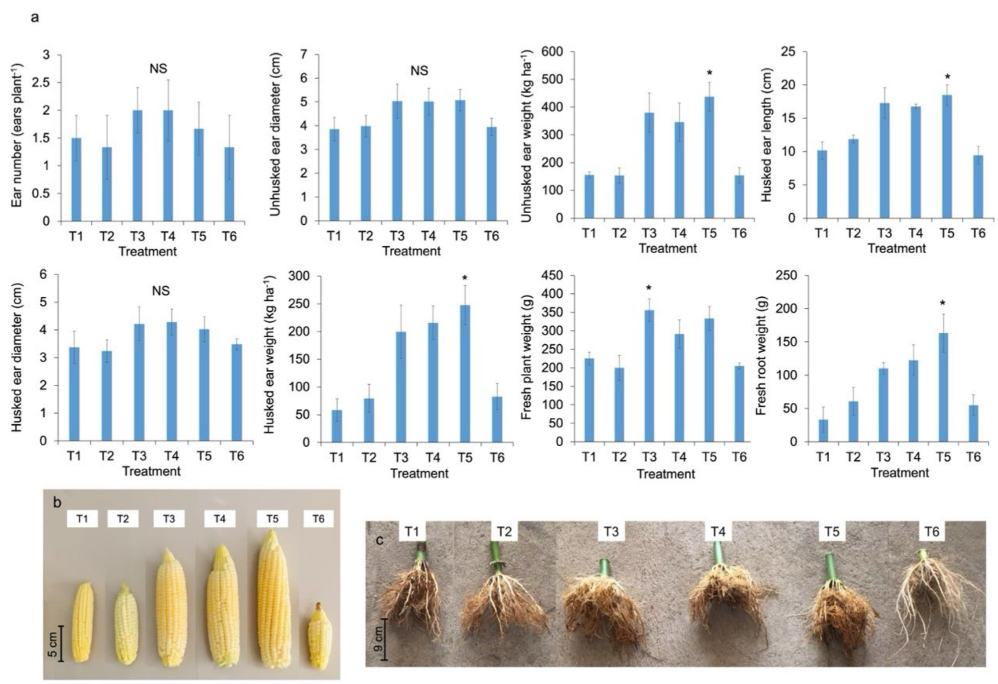


**Figure 3.** Yield of sweet corn with application of chemical fertilizers according to soil analysis (CF) and in combination with different residues from the black solider fly (BSF) raised using chicken feed (ChF), tofu meal (TM), pineapple peel (PP), cassava meal (CM) and dry chicken manure (DCM). Ear number, unhusked ear diameter, unhusked ear weight, husked ear length, husked ear diameter, husked ear weight, fresh plant weight and fresh root weight of sweet corn (a), husked ear character (b) and fresh root biomass (c) are shown. Statistically significant differences are indicated with * (P < 0.05) and NS = not significant. Th error bar shows standard deviation. T1: 75% CF, T2: 75% CF + 25% ChF, T3: 75% CF + 25% TM, T4: 75% CF + 25% PP, T5: 75% CF + 25% CM and T6: 75% CF + 25% DCM

Although the residues obtained from the raising of BSF did not pass the Thai organic fertilizer standards for commercial registration, they can still be used for plantation because they possess remarkable properties as organic fertilizers. The residues based on cassava meal produced plants with a high seed germination index. This is in agreement with earlier reports in which it was observed that seeds treated with the BSF frass fertilizer presented the highest seed germination rate > 90% and improved soil health and crop yields (Beesigamukama et al., 2022; Tanga et al., 2022). The residues from BSF raising were tested for growing sweet corn in greenhouse conditions. The highest stem diameter was found for the application of 75% CF + 25% residue from BSF raised on tofu meal. The unhusked ear weight, husked ear length, husked ear weight and fresh root weight of sweet corn were highest for 75% CF + 25% residue from BSF raised on cassava meal. These results were in accordance with the findings that BSF frass fertilizer improved the heights of plants, chlorophyll concentrations, N uptake, and maize yields (Beesigamukama et al., 2020) and affected the growth of Swiss chard (Chirere et al., 2021). Application of a combination of BSF frass fertilizer and chemical fertilizers produced higher yields than chemical fertilizers alone for tomatoes, kale, and French beans. Moreover, the combined application produced vegetables with high crude protein levels (Anyega et al., 2021). This research suggests that the combination of chemical fertilizers with BSF residues improves the growth and yields of sweet corn and can potentially reduce the use of chemical fertilizers by 25%.

## 4. Conclusions

Residues from BSF cultivation can be used as organic fertilizers in a zero-waste system as the BSF larvae decomposed agro-industrial waste and produced residues rich in organic matter that improved the soil fertility for sweet corn cultivation. The nutrient content of these residues depended on the feed substrate. Tofu meal had a high protein content and other nutrients that allowed the BSF to rapidly decompose it. A mix of chicken feed, dry chicken manure, and pineapple peels is recommended to obtain residues containing a complete range of nutrients, including nitrogen, phosphorus, and potassium. Residues from cassava meal (25%), with the highest germination index, complement chemical fertilizers (75%) and thus, can be used in integrated nutrient management to enhance sweet corn yields. To ensure optimal use, residues should be fully decomposed and fermented with other organic materials in order to meet the organic fertilizer standards for commercial applications in Thailand.

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## 6. Authors' Contributions

Sirinapa Chungopast designed research and coordinated research; Supphawed Tussanakit performed research; Roungthip Masmeatathip supported resources; Sirinapa Chungopast and Chanwit Kaewtapee analyzed data; Yoshiki Matsumoto, Kiyonori Kawasaki and Mika Nomura provided provided research advice, review, and editing; and Supphawed Tussanakit and Sirinapa Chungopast wrote the paper.

## 7. Conflicts of Interest

The authors declare that there are no conflicts of interest

**ORCID**

Supphawed Tussanakit https://orcid.org/0009-0000-2680-673X

Sirinapa Chungopast https://orcid.org/0000-0002-8856-3275

Chanwit Kaewtapee https://orcid.org/0000-0001-8565-3809

Roungthip Masmeatathip https://orcid.org/0000-0001-5022-6997

Yoshiki Matsumoto https://orcid.org/0000-0002-8620-2863

Kiyonori Kawasaki https://orcid.org/0000-0003-1572-6341

Mika Nomura https://orcid.org/0000-0003-3038-8336

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