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The Effects of Pre-Composting Subjected to Black Soldier Fly Larvae Digestion on Agri-Food Waste Maturation Indicators

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ABSTRACT

The increasing demand for sustainable agricultural practices has led to the exploration of alternative composting methods, including the use of black soldier fly larvae (BSFL) for managing organic waste. This study compares the physical, chemical, nutrient, and nutrient loss properties of frass produced through two treatments at specified moisture contents of 65 and 80%, respectively (BSFL-65 and BSFL-80). The physical properties, including yield, water holding capacity, bulk density, and moisture content, were analyzed, revealing no significant differences between the treatments for yield, water holding capacity, and bulk density. However, moisture content was significantly higher in BSFL-80, indicating a distinct impact of treatment on water retention. In terms of chemical properties, the pH of BSFL-80 was significantly higher than that of BSFL-65, while electrical conductivity showed a significant difference at the borderline. Total dissolved solids were significantly higher in BSFL-80, whereas total volatile solids were significantly higher in BSFL-65. Nutrient content analysis revealed no significant differences in carbon (C), hydrogen (H), sulfur (S), nitrogen (N), phosphorus (P), potassium (K), and other elements, except for ammonia nitrogen, which was slightly higher in BSFL-80. Nutrient loss assessments showed no significant differences between the treatments for C, H, S, N, P, K, calcium, magnesium, copper, or zinc. These findings suggest that while certain chemical and physical properties, such as moisture content and pH, are significantly

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influenced by the treatment type, the overall nutrient composition and nutrient loss were largely unaffected by the treatment variations. This study provides valuable insights into the comparative efficacy of BSFL-based frass treatments, offering potential implications for sustainable agricultural practices and waste management.

Keywords: BSFL, frass, nutrient, moisture-content, pre-composting

INTRODUCTION

Municipal solid waste (MSW) comprises 20 categories, including food waste, plastic, paper, and glass (Jalil, 2010). Among these, Food waste represents a significant global challenge, with approximately one-third of food produced for human consumption lost or wasted annually, leading to severe economic, social, and environmental repercussions (Mokrane et al., 2023). The economic cost of food waste reaches billions, impacting households and the entire supply chain, while socially, this waste starkly contrasts with the millions suffering from hunger (Raina & Bathla, 2024). Environmentally, food waste contributes to greenhouse gas emissions and resource depletion, with avoidable consumer food waste (ACFW) alone responsible for substantial emissions and land use (Coudard et al., 2024). Effective management strategies, including consumer education and innovative practices like anaerobic digestion and composting, are essential for mitigating these impacts (Trivedi et al., 2023). As awareness grows, addressing the multifaceted drivers of food waste—from cultural to economic factors—becomes crucial for global sustainability and food security (Raina & Bathla, 2024).

Composting food waste using BSFL has emerged as an effective method for waste reduction and organic fertilizer production. Studies indicate that BSFL can significantly degrade organic matter, with one study reporting a substrate reduction of 87.95% when 2000 larvae were applied to 20 kg of kitchen waste over 22 days (Mohod et al., 2024). The larvae consume food waste efficiently and enhance the resulting compost's nutritional profile, which meets agricultural standards for essential nutrients like N, P, and K (Putri et al., 2024). Furthermore, optimal conditions such as larval density and environmental factors can improve waste reduction rates, with some studies achieving reductions of up to 84.5% in organic waste (Amin et al., 2024). Overall, utilizing BSFL for composting presents a sustainable alternative to traditional waste management practices, contributing to both waste diversions from landfills and the production of high-quality organic fertilizers (Hariri et al., 2024).

Recent studies have also shown the promise of BSFL frass, the by-product of larvae, as a biofertilizer. For instance, basil plants grown with BSFL frass showed substantial growth when compared to those grown with synthetic fertilizers, although some deficiencies were noted, such as lower levels of manganese (Mn), calcium (Ca), and zinc (Zn) (Romano et al., 2024). Additionally, BSFL frass has been demonstrated to provide adequate nutrients for lettuce growth, reducing the need for additional fertilizer applications after the initial growth cycle (Chiam et al., 2021). Furthermore, research has highlighted that BSFL frass is a suitable soil amendment, promoting plant growth while maintaining environmental safety, with no heavy metal contamination or pathogens found in the frass (Chiam et al., 2021). In a comparative study, the application of BSFL frass to Pakchoi resulted in greater biomass production than chemical fertilizers, supporting its potential as a viable alternative to synthetic fertilizers in sustainable agriculture (Agustiyani et al., 2021). These findings reinforce the potential of BSFL frass as a nutrient-rich and environmentally safe amendment, enhancing the role of BSFL in organic waste management.

Moisture content in food waste significantly influences its management and processing, with varying optimal levels identified across different studies. For instance, raw food waste typically contains around 40% moisture, which can be effectively treated using self-sustaining smoldering techniques, achieving over 90% mass destruction (Song et al., 2022). In composting, a moisture content of approximately 60% is optimal for maintaining peak temperatures and minimizing odor emissions (Rose et al., 2019). Conversely, studies indicate that moisture levels below 40% are preferable to mitigate odor production during decomposition (Qamaruz-Zaman et al., 2019). Pre-treatment methods, such as hot water washing, can reduce the moisture content from 76.7 to 48.9%, enhancing drying efficiency and environmental sustainability (Aziz & Qaisari, 2024).

Moisture content is a critical factor influencing the growth and survival of BSFL, *Hermetia illucens*, as it directly affects their performance on various substrates. Research indicates that optimal moisture levels enhance larval growth, with studies showing that larvae reared at 70% moisture exhibited superior growth metrics compared to those at lower levels (Okpoko et al., 2024). Additionally, moisture influences both larval survival and pupation rates, with higher moisture levels significantly reducing prepupal mortality and promoting deeper pupation (Liu et al., 2023). Furthermore, the water-release properties of substrates play a vital role, as substrates with appropriate moisture content correlate with increased larval survival (Frooninckx et al., 2024). The moisture content of food waste can also affect the efficiency of residue separation from the insect biomass, which is an important consideration for waste management and bioconversion technologies. Studies have shown that moisture contents of 70 and 75% facilitate effective residue separation through sieving, while higher moisture contents pose challenges to this process (Cheng et al., 2017).

Moreover, the specific moisture content of substrates has been linked to the growth and metabolic performance of BSFL. A study examining substrate moisture content from 45 to 85% found that larvae developed best at moisture contents ranging from 45 to 75%, with the highest growth rate observed at 45% moisture content. The performance of BSFL was found to be indirectly influenced by substrate moisture due to microbial processes that co-occur with larval development (Bekker et al., 2021). Overall, maintaining adequate moisture levels is essential for maximizing the efficiency of BSFL in waste conversion processes, thereby supporting their potential as a sustainable protein source.

This study evaluates the feasibility and effectiveness of using BSFL as a sustainable approach for processing food waste, mainly fruits and vegetables, into nutrient-dense compost. By testing different moisture levels (65 and 80%, respectively), this study seeks to identify optimal conditions that enhance the nutrient content and quality of the resulting compost. Through a comprehensive analysis of physicochemical and nutritional properties, this research aims to establish frass produced by BSFL as a viable alternative for food waste management, thereby supporting agricultural productivity and environmental sustainability.

MATERIALS AND METHODS

Source of Materials and Processing

The food waste for this experiment was collected from HERO and BIG supermarkets in Sri Serdang, Selangor (Malaysia), and the local market. The food waste composition comprised spoiled vegetables and fruits, including cabbage, cucumber, tomato, banana, and papaya, at a ratio of 1:1. A total of 20 kg of food waste was collected. To ensure uniformity in the frass process, the size of the food waste was cut within the range of 2 to 3 cm.

The food waste was thermally pre-treated using an oven dryer at 70°C to achieve a moisture content of 60%. After the pre-treatment, the food waste was divided into three samples, each weighing 625 g, and mixed with garden soil in a ratio of 5:3 (food waste: garden soil). Once combined with the garden soil, the samples were poured into separate composting boxes sized 30 cm in length, 10 cm in height, and 12 cm in width to accommodate the mixture effectively. To initiate the pre-composting phase, water was added to each sample to achieve the specified moisture contents of 65 and 80%, respectively. The moisture content of the samples was monitored every two days using a soil moisture detector, and adjustments were made by adding water as needed to maintain the desired levels. Additionally, each composting box was covered with newspapers to prevent insect access, such as flies.

BSFL Digestion

Live BSFL was purchased online (Lazada, Malaysia) under the Biovae shop. The larval density was 1 – 2.5 larvae/g, and the weight was 0.2 ± 0.1 g. After the pre-composting phase, 20 g of BSFL was added to each composting box. To prevent contact with insects, all samples were covered with newspaper, ensuring the BSFL could decompose the food waste without interference. The composting boxes were kept in a low-light-intensity area for 15 days. The frass was harvested using a 2 mm sieve tray after the composting period. The frass containing the organisms was filled approximately one-third of the way in the sieve tray. The tray was gently shaken from side to side, similar to sifting flour. As a result, the frass fell through the sieve. This sifting method was repeated until all samples were processed, ensuring the frass had a consistent texture and reducing its particle size from coarse to fine.

Physical Properties of Frass

The yield of frass produced was calculated by measuring the weight, which was then divided by the amount of food waste used. Water holding capacity of frass was measured using the following equation.

$$WHC = \frac{(Ws - Wi) + MC \times Wi}{(1 - MC) \times Wi}$$

Where, WHC = Water holding capacity (g water per g dry compost); W_i = Initial weight of frass (before filtration); W_s = Final weight of frass (after filtration); MC = Moisture content of frass

The bulk density of the frass and soil was measured by filling 150 g of frass into a 10 L container. The compost was then compressed until no large void spaces remained, and the volume occupied was measured. The bulk density was calculated by dividing the weight of the frass by the volume occupied (kg/m^3).

Chemical Properties of Frass

A total of 20 g of the frass sample was weighed and placed in a 100 ml beaker. Subsequently, 20 ml of distilled water was added to the beaker, and the mixture was stirred continuously for 15 min. The beaker was then covered and allowed to stand undisturbed for 30 min. After the settling period, a pH meter was carefully inserted into the liquid region of the sample solution to measure and record the pH value. Electrical conductivity (EC) was measured using a portable EC detector (SBPHM001, OEM, China). Total dissolved solids (TDS) were measured using a portable TDS meter (TDS-3, China).

The total volatile solids (TVS) content in the frass was determined based on the results of the moisture content test. Initially, the frass samples were heated to a temperature of 105°C, as per the moisture content test procedure. Following this, the samples were subjected to ashing in a furnace at a temperature of 550°C for a duration of 4 hr. After the ashing process, the remaining ash was weighed, and this mass was used to represent the TVS content in the frass (Vijayan et al., 2024).

Nutrient Content

The elements in frass were analyzed using an auto analyzer and an atomic absorption spectrophotometer (AAS) (AAnalyst200, PerkinElmer, USA). The macro and micro-elements measured included C, H, N, K, P, Ca, magnesium (Mg), Zn, copper (Cu), and S.

For the determination of C, H, N, and S concentrations, solid samples of frass were sent to the Material Characterization Laboratory, Faculty of Engineering, Universiti Putra Malaysia (UPM). To measure the concentrations of P, K, Ca, Mg, Cu, and Zn, the samples were analyzed at Analytical Laboratory 2, Faculty of Agriculture, UPM, using an AAS.

The samples were prepared in liquid form using the dilute double acid (DDA) method. Specifically, 5.0 g of each sample was weighed and placed into a Falcon tube, followed by the addition of 25 ml of DDA extracting reagent. The DDA extracting reagent was prepared in the laboratory by mixing hydrochloric acid (HCl, 37%, Merck, Germany) and sulfuric acid (H_2SO_4, 98%, Sigma-Aldrich, USA) to obtain final concentrations of 0.05 N HCl and 0.025 N H_2SO_4, respectively. The falcon tube was shaken for 15 min using an end-to-end shaker at 180 rpm. Subsequently, the solution was filtered through filter paper, and the filtrate was collected in a 50 ml plastic vial. The filtrate was then sent for analysis using an AAS.

The calculation for ammoniacal nitrogen was as follows:

$$NH4 - N = \frac{Vs \ \times M \ \times 0.014 \ \times 100}{W}$$

Where, Vs = Volume of sulfuric acid used for sample titration; M = Molarity of sulfuric acid; W = Weight of dry soil sample

Nutrient Losses

A sieve tray was prepared for the extraction of nutrients from frass. To prevent the loss of compost material during the process, a layer of muslin cloth was securely placed inside the sieve tray. The muslin cloth acted as a filter, allowing water to pass through while retaining the solid compost particles. A uniform layer of frass, approximately 2.5 cm thick, was evenly spread over the muslin cloth in the sieve tray. Following this, 500 ml of distilled water was carefully poured onto the frass layer. The distilled water was used to ensure that no external contaminants interfered with the nutrient extraction process. As the distilled water percolated through the frass layer, it carried dissolved nutrients with it. The excess water, along with the leached nutrients, passed through the muslin cloth and sieve tray. This leachate was collected in a clean, empty container positioned beneath the sieve tray to ensure no loss of the extracted solution. The collected leachate was then subjected to nutrient analysis to determine the concentration and composition of the dissolved nutrients.

Statistical Analysis

All statistical analyses were performed using Python (3.13.0). Descriptive statistics were computed for all measured parameters. The normality of data distribution was assessed using the Shapiro-Wilk test. An independent samples *t*-test was conducted to compare the means of variables between the two treatments (BSFL-1-65 and BSFL-1-80). A significance level of $p < 0.05$ was considered statistically significant.

RESULTS

Physical Properties

The physical properties of two treatments, BSFL-1-65 and BSFL-1-80, were assessed based on four factors: yield (%), water holding capacity (g/g), bulk density (kg/m^3), and moisture content (%). For yield (%), the results were relatively similar across both treatments, with BSFL-1-65 showing a range from 48.76 to 50.88%, and BSFL-1-80 ranging from 49.15 to 51.88% as shown in Figure 1a. The *t*-test for yield revealed no significant difference between the two treatments (*t*-statistic = -0.6020, *p*-value = 0.5796). Water holding capacity also showed minimal variation between the two groups, with values ranging from 3.31 to 3.43 g/g for BSFL-1-65 and 3.35 to 3.43 g/g for BSFL-1-80 (Figure 1b). The t-test

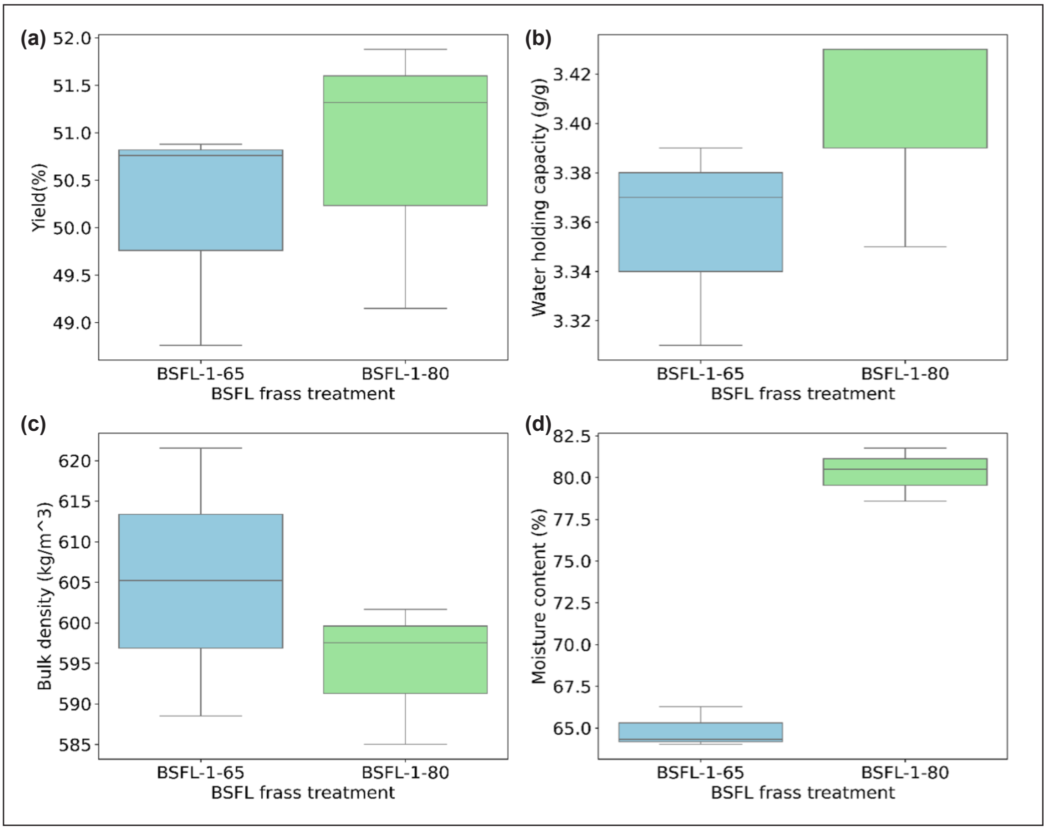

Figure 1. Physical properties of frass: comparison of yield percentage, water holding capacity, bulk density, and moisture content between BSFL-1-65 and BSFL-1-80 treatments
Note. BSFL = Black soldier fly larvae; No significant differences were observed across the physical properties ($p > 0.05$)

for this parameter also indicated no significant difference (*t*-statistic = -1.2999, *p*-value = 0.2635). Bulk density measurements were found to range from 588.51 to 621.53 kg/m³ for BSFL-1-65, and 585.02 to 601.65 kg/m³ for BSFL-1-80, with the *t*-test showing no significant difference between the treatments (*t*-statistic = 0.9611, *p*-value = 0.3909) (Figure 1c). However, significant differences were observed for moisture content (%), with BSFL-1-65 ranging from 64.03 to 66.29% and BSFL-1-80 ranging from 78.59 to 81.76% (Figure 1d). The *t*-test for moisture content yielded a highly significant result (*t*-statistic = -13.2477, *p*-value = 0.0002), indicating a marked difference between the two treatments. This suggests that moisture content is the only physical property significantly affected by the treatment type.

Chemical Properties

The chemical properties of two treatments, BSFL-1-65 and BSFL-1-80, were assessed based on pH, EC, TDS, and TVS. For pH, the results were quite similar across both treatments, with BSFL-1-65 ranging from 6.68 to 6.70, and BSFL-1-80 from 6.72 to 6.75 (Figure 2a). The *t*-test revealed a statistically significant difference in pH between the two treatments

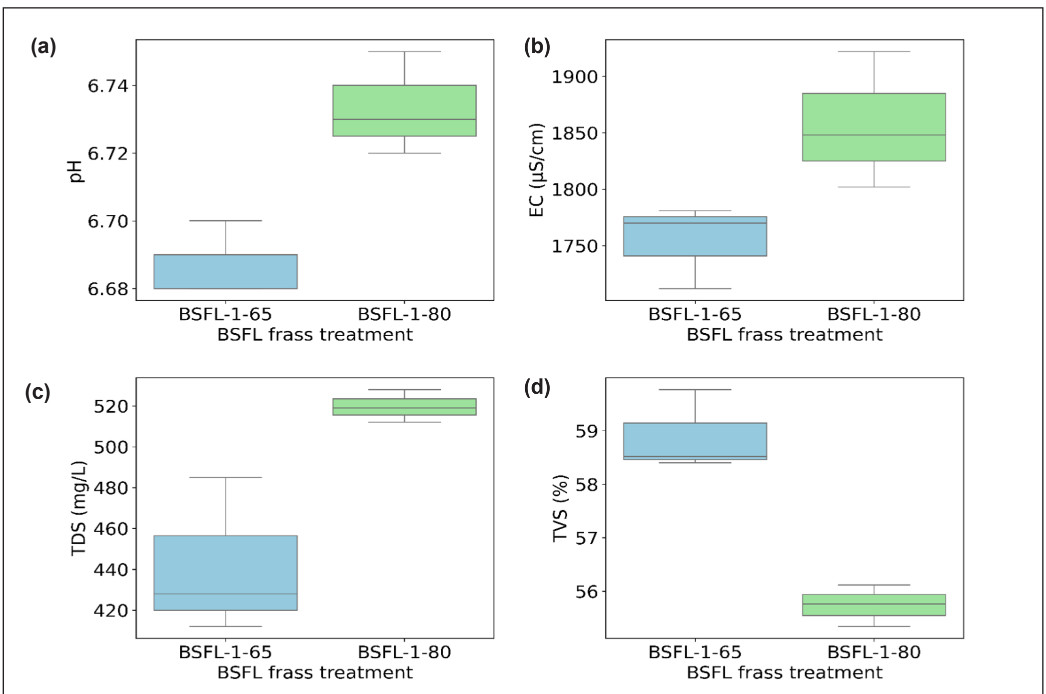

Figure 2. Chemical properties of frass: comparison of pH, electrical conductivity (EC), total dissolved solids (TDS), and total volatile solids (TVS) between BSFL-1-65 and BSFL-1-80 treatments
Note. BSFL = Black soldier fly larvae; Significant differences were observed in pH and TDS, with no significant differences in EC and TVS ($p < 0.05$)

(t-statistic = -4.2212, p-value = 0.0135), suggesting that the treatment notably influenced pH. EC values for BSFL-1-65 ranged from 1712 to 1781 µS/cm, while BSFL-1-80 ranged from 1802 to 1922 µS/cm (Figure 2b). The t-test for EC showed a borderline significance (t-statistic = -2.5130, p-value = 0.0658), indicating that while the difference between treatments is noticeable, it is not statistically strong at the conventional significance level. TDS values followed a similar trend, with BSFL-1-65 ranging from 412 to 485 mg/L and BSFL-1-80 ranging from 512 to 528 mg/L (Figure 2c). The t-test for TDS revealed a significant difference (t-statistic = -3.4464, p-value = 0.0261), indicating that TDS levels were significantly higher in BSFL-1-80. Lastly, TVS values ranged from 56.12 to 59.77% for BSFL-1-65 and from 55.34 to 55.76% for BSFL-1-80 (Figure 2d). The t-test for TVS showed a significant result (t-statistic = 6.4079, p-value = 0.0030), with BSFL-1-65 showing notably higher TVS values compared to BSFL-1-80. This suggests that TVS is the most significantly affected chemical property by the treatment type.

Nutrient Content

The nutrient content of frass from the BSFL-1-65 and BSFL-1-80 treatments was assessed across several parameters, including C, H, S, N, P, K, ammonia nitrogen (NH_3-N), Ca, Mg, Cu, Zn, carbon-to-nitrogen ratio (C/N), and nitrogen-to-phosphorus-to-potassium ratio (NPK). The C content for BSFL-1-65 ranged from 35.76 to 37.49%, while BSFL-1-80 ranged from 35.34 to 36.34%, with no significant difference between the two treatments (t-statistic = 1.1073, p-value = 0.3303) (Figure 3a). Similarly, H content varied from 2.32 to 2.66% in BSFL-1-65 and from 2.41 to 2.76% in BSFL-1-80, but this difference was not statistically significant (t-statistic = -0.4246, p-value = 0.6929) (Figure 3b). S levels ranged from 0.16 to 0.19% for BSFL-1-65 and 0.15 to 0.18% for BSFL-1-80, with no significant difference found (t-statistic = 1.2500, p-value = 0.2794) (Figure 3c). N concentrations were slightly higher in BSFL-1-65, ranging from 1.28 to 2.09%, compared to BSFL-1-80, which ranged from 1.31 to 2.12%, but the difference was not statistically significant (t-statistic = -0.1802, p-value = 0.8658) (Figure 3d). For P, values ranged from 1073.89 to 1739.60 mg/L in BSFL-1-65 and 1008.66 to 1835.84 mg/L in BSFL-1-80, with no significant differences observed (t-statistic = -0.2255, p-value = 0.8326) (Figure 3e). K concentrations ranged from 958.76 to 1739.60 mg/L in BSFL-1-65 and 1008.66 to 1835.84 mg/L in BSFL-1-80, also showing no significant difference (t-statistic = -0.3273, p-value = 0.7599) (Figure 3f). NH_3-N levels were slightly higher in BSFL-1-80, ranging from 49.91 to 65.29 mg/L, compared to BSFL-1-65 (52.47 to 64.10 mg/L), though the difference was not statistically significant (t-statistic = 0.0933, p-value = 0.9302) (Figure 3g). Ca content ranged from 3.29 to 6.88 mg/L in BSFL-1-65 and 5.95 to 7.18 mg/L in BSFL-1-80, with no significant difference (t-statistic = -1.0508, p-value = 0.3527) (Figure 3h). Mg levels in BSFL-1-65 ranged from 5.55 to 9.44 mg/L, while in

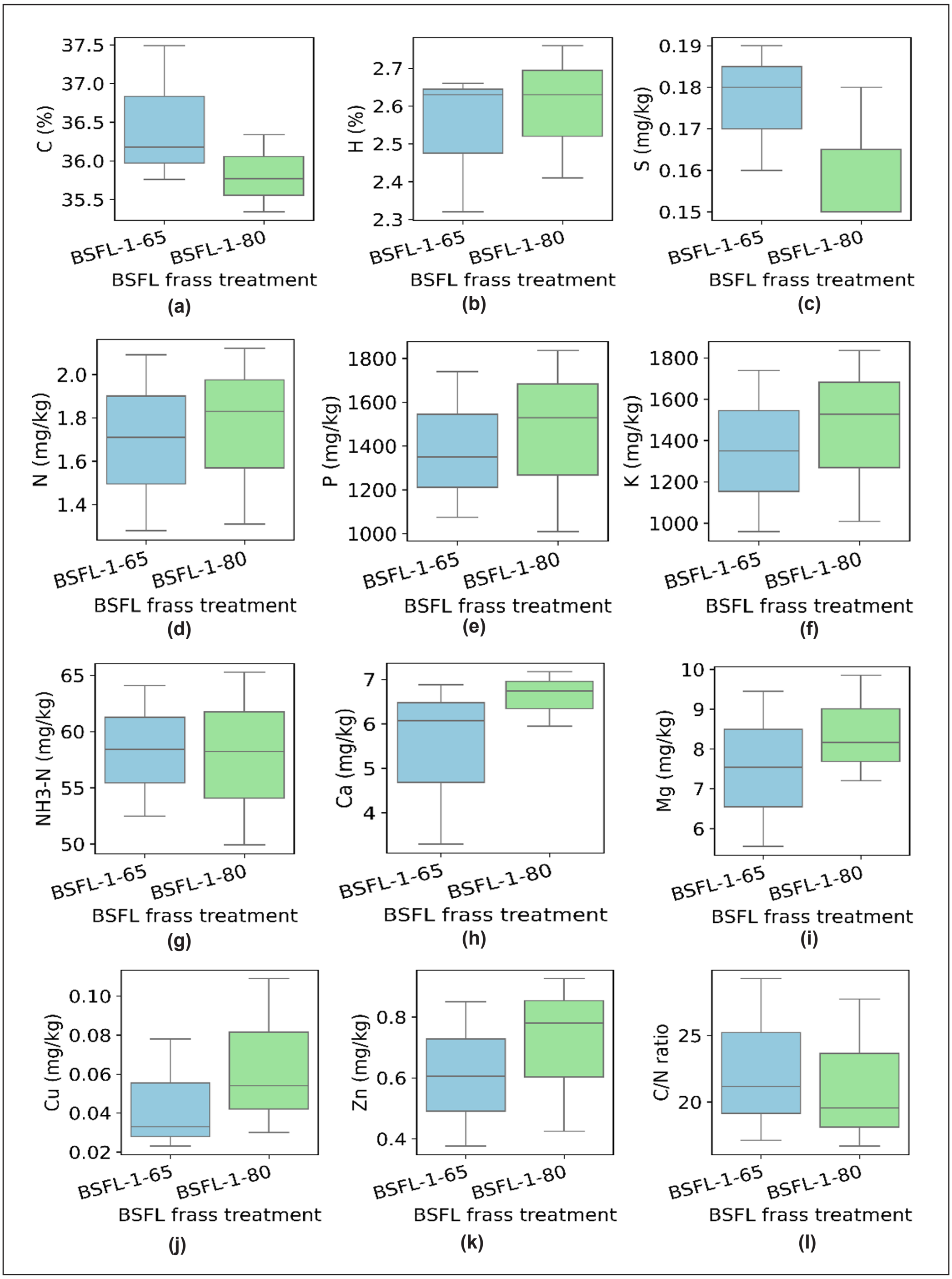

Figure 3. Nutrient content of frass: comparison of carbon (C), hydrogen (H), sulfur (S), nitrogen (N), phosphorus (P), potassium (K), ammonia nitrogen (NH_3-N), calcium (Ca), magnesium (Mg), copper (Cu), zinc (Zn), and carbon-to-nitrogen (C/N) ratio between BSFL-1-65 and BSFL-1-80 treatments

Note. BSFL = Black soldier fly larvae; No significant differences were found in the nutrient content ($p > 0.05$)

BSFL-1-80, they ranged from 7.20 to 9.85 mg/L, with no significant difference (t-statistic = -0.6564, p-value = 0.5474) (Figure 3i). Cu content was slightly higher in BSFL-1-80, ranging from 0.03 to 0.11 mg/L, compared to 0.023 to 0.078 mg/L in BSFL-1-65, though no significant difference was observed (t-statistic = -0.6815, p-value = 0.5330) (Figure 3j). Zn levels ranged from 0.376 to 0.85 mg/L in BSFL-1-65 and from 0.425 to 0.93 mg/L in BSFL-1-80, with no statistically significant difference (t-statistic = -0.4931, p-value = 0.6478) (Figure 3k). Finally, the C/N ratio ranged from 17.11 to 29.29 in BSFL-1-65 and from 16.67 to 27.74 in BSFL-1-80, with no significant difference (t-statistic = 0.2459, p-value = 0.8179) (Figure 3l).

The NPK ratio for both treatments remained consistent around 19:1:1 for BSFL-1-65 and 21:1:1 for BSFL-1-80, showing no significant difference in their composition (Table 1).

Table 1
NPK ratio of frass from BSFL-1-65 and BSFL-1-80 treatments

Treatment	NPK ratio
BSFL-65	19.2:1:1
	20.9:1:1
	20.4:1:1
BSFL-80	21.6:1:1
	20:1:1
	20.1:1:1

Note. NPK = Nitrogen-to-phosphorus-to-potassium ratio; BSFL = Black soldier fly larvae

Nutrient Loss

The nutrient loss content of frass from two treatments, BSFL-1-65 and BSFL-1-80, was evaluated across various parameters, including C, H, S, N, P, K, NH_3-N, Ca, Mg, Cu, and Zn. The results demonstrated no significant differences between the two treatments for any of the evaluated nutrients (Figure 4). Specifically, C loss ranged from 0.156 to 0.178% for BSFL-1-65 and 0.157 to 0.172% for BSFL-1-80 (t = 0.1541, p = 0.8860), while H loss ranged from 0.062 to 0.071% for BSFL-1-65 and 0.061 to 0.069% for BSFL-1-80 (t = 0.2683, p = 0.8021). S loss was 0.064 to 0.072% for BSFL-1-65 and 0.061 to 0.071% for BSFL-1-80 (t = -0.1250, p = 0.9080), and N loss ranged from 2.777 to 4.46% for BSFL-1-65 and 2.639 to 5.133% for BSFL-1-80 (t = -0.1480, p = 0.8905). For P, the loss was 1.08 to 3.015% for BSFL-1-65 and 1.08 to 2.418% for BSFL-1-80 (t = 0.3699, p = 0.7322). K loss ranged from 0.89 to 1.76% for BSFL-1-65 and 0.759 to 1.539% for BSFL-1-80 (t = 0.3837, p = 0.7211). NH_3-N loss varied from 5.047 to 8.109 mg/L for BSFL-1-65 and 4.786 to 9.308 mg/L for BSFL-1-80 (t = -0.1411, p = 0.8956). Ca loss was 0.287 to 0.529 mg/L for BSFL-1-65 and 0.292 to 0.56 mg/L for BSFL-1-80 (t = 0.5449, p = 0.6173). Mg loss ranged from 0.0558 to 0.0930 mg/L for BSFL-1-65 and 0.0620 to 0.0910 mg/L for BSFL-1-80 (t = 0.0790, p = 0.9409). Cu loss varied from 0.023 to 0.078 mg/L for BSFL-1-65 and 0.03 to 0.11 mg/L for BSFL-1-80 (t = 0.2403, p = 0.8227). Finally, Zn loss ranged from 0.333 to 0.505 mg/L for BSFL-1-65 and 0.315 to 0.409 mg/L for BSFL-1-80 (t = 0.6761, p = 0.5474).

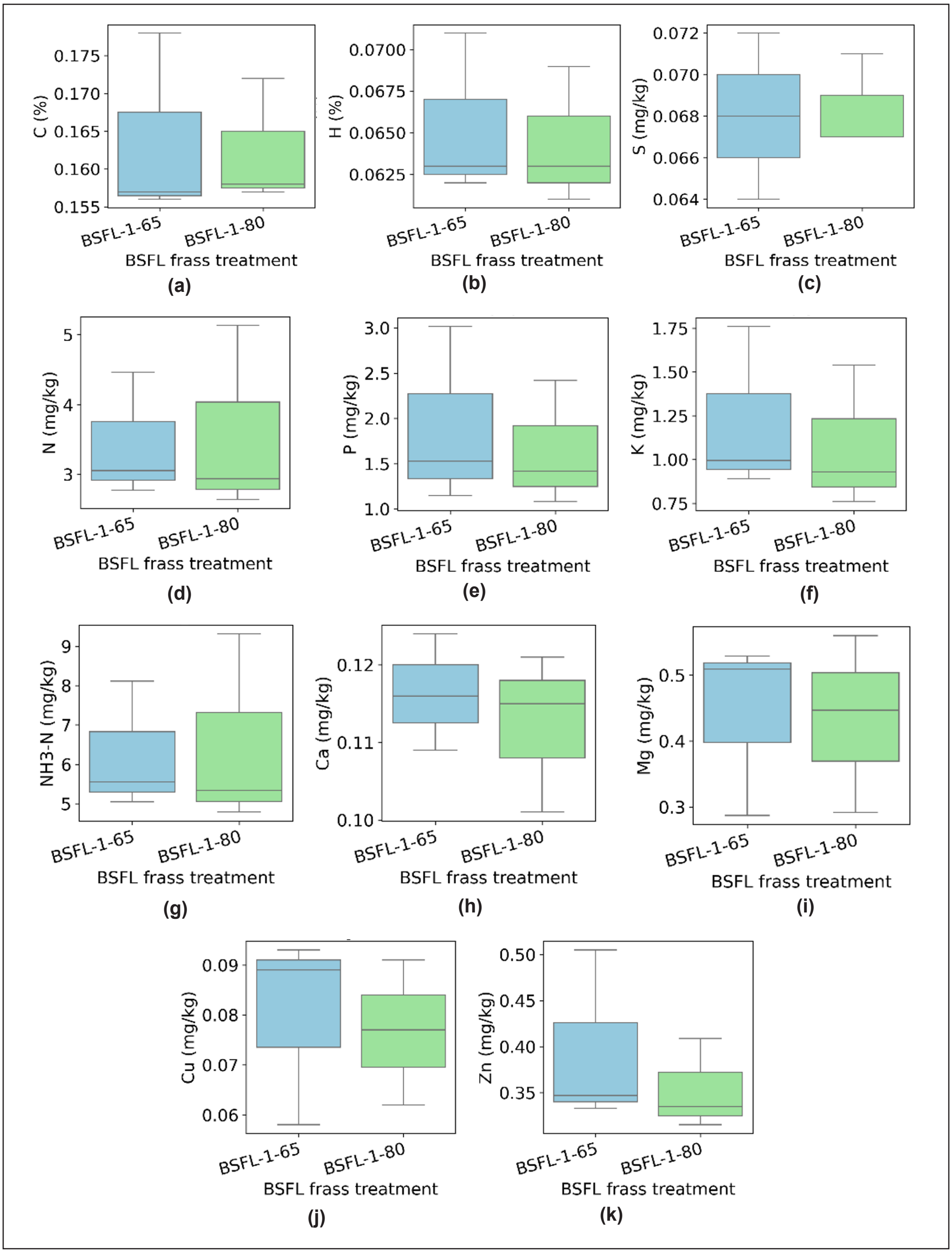

Figure 4. Nutrient loss content of frass: comparison of nutrient loss carbon (C), hydrogen (H), sulfur (S), nitrogen (N), phosphorus (P), potassium (K), ammonia nitrogen (NH_3-N), calcium (Ca), magnesium (Mg), copper (Cu), and zinc (Zn) between BSFL-1-65 and BSFL-1-80 treatments

Note. BSFL = Black soldier fly larvae; No significant differences were observed in nutrient loss across all parameters ($p > 0.05$)

DISCUSSION

In this study, the physical properties of two treatments, BSFL-1-65 and BSFL-1-80, were thoroughly evaluated based on yield (%), water holding capacity (g/g), bulk density (kg/m³), and moisture content (%), revealing significant differences in moisture content, while other parameters showed no significant variations between the treatments. Higher moisture content (80%) tends to enhance microbial activity, leading to improved degradation rates and higher yields, as microorganisms thrive in optimal moisture conditions, facilitating aerobic decomposition (Zavala & Funamizu, 2005). Conversely, at lower moisture levels (65%), the composting process may experience reduced biological activity, resulting in lower yields and diminished water holding capacity due to increased bulk density, which can hinder the compost's ability to retain moisture (Shyamala & Belagali, 2012; Zailani, 2018). Additionally, studies indicate that excessive moisture can lead to anaerobic conditions, negatively impacting compost quality and stability (Khater, 2012).

Varying moisture levels can influence the water holding capacity of frass, which is crucial for its application in irrigation systems. Research indicates that higher moisture content enhances the biodegradation rates of organic materials, leading to improved compost quality and water retention properties (Zavala & Funamizu, 2005). Compost application has been shown to increase soil water retention, with studies demonstrating that organic amendments can enhance water storage capacity, particularly in sandy soils (Le Guyader et al., 2024; Zemánek, 2014). For instance, a combination of biochar and compost resulted in a notable increase in water holding capacity, with optimal mixtures achieving substantial improvements in soil moisture retention (de Jesus Duarte et al., 2022). Furthermore, the effectiveness of compost in retaining moisture is influenced by its composition and the soil's textural characteristics, suggesting that higher moisture levels can further optimize the benefits of compost in irrigation systems (Negara et al., 2023; Zemánek, 2014).

Varying moisture content significantly influences water holding capacity and bulk density in frassing, with distinct effects observed at 65 and 80% moisture levels, respectively. At 65% moisture, composting processes tend to exhibit enhanced microbial activity, leading to accelerated organic matter degradation and improved humification, as evidenced by higher temperatures and microbial interactions (Sun et al., 2024). Conversely, at 80%, while microbial activity remains, the increased moisture can lead to reduced oxygen availability, potentially hindering aerobic processes and resulting in lower overall compost quality (Kim et al., 2015). Studies indicate that optimal moisture levels, typically around 70-75%, balance microbial efficiency and physical structure, promoting effective composting while minimizing greenhouse gas emissions (Zavala & Funamizu, 2005). Thus, maintaining an appropriate moisture content is crucial for optimizing composting outcomes, as it influences both water retention and bulk density.

For the chemical properties, both treatments, BSFL-1-65 and BSFL-1-80, were evaluated based on pH, EC, TDS, and TVS, revealing significant differences in pH, TDS, and TVS. At the same time, EC exhibited a borderline significant difference between the treatments. At higher moisture levels, studies indicate that pH tends to stabilize within a neutral range, while EC and TDS values generally increase, reflecting enhanced solubility of nutrients and minerals, which is crucial for microbial activity and nutrient availability (Ajaweed et al., 2022; Khater, 2012). For instance, vermicomposting at 78% moisture resulted in higher mineral N content and microfauna biomass, suggesting that moisture levels above 65% promote better nutrient cycling and microbial growth (Qin et al., 2021). Additionally, the total volatile solids decrease as moisture content increases, indicating more efficient decomposition processes at elevated moisture levels (Ojo et al., 2018). Research indicates that higher moisture content, such as 80%, tends to enhance microbial activity, leading to improved N mineralization and higher biomass of beneficial microfauna, which can positively influence compost quality (Qin et al., 2021). Additionally, moisture levels impact pH stability, with studies showing that compost remains alkaline throughout the process, which is crucial for nutrient availability (Ameen et al., 2016). Furthermore, moisture content affects the degradation rates of organic matter, with optimal levels facilitating better breakdown of total organic carbon and volatile solids, thereby enhancing compost maturity (Zailani, 2018; Zavala & Funamizu, 2005).

Variations in moisture content significantly influence the nutrient composition of frass, with optimal levels enhancing microbial activity and nutrient availability. Studies indicate that moisture contents around 70 to 75% facilitate better composting outcomes, promoting higher temperatures and microbial interactions that enhance organic matter degradation and nutrient retention, particularly N forms like Kjeldahl-N and nitrate-N (Sun et al., 2024). For instance, a moisture content of 75% was found to optimize temperature increases and nutrient profiles, while lower moisture levels (below 65%) hindered aerobic decomposition and nutrient retention (Palsania et al., 2008; Zavala & Funamizu, 2005). Conversely, excessively high moisture levels (e.g., 80%) can lead to diminished microbial efficiency and increased greenhouse gas emissions, particularly nitrous oxide (N_2O) (Shi et al., 2012).

Moisture content significantly influences the NPK ratio, C/N ratio, and nutrient dynamics during composting processes. Higher moisture levels, such as 65%, have been shown to reduce gas emissions and nutrient losses, thereby enhancing nutrient retention, including N content, which increased by 33.3% during composting (Ghanney et al., 2021). The C/N ratio is also affected; for instance, chicken manure composting achieved a C/N ratio of 10, indicating optimal conditions for microbial activity. Additionally, initial moisture content impacts the degradation of organic matter, with studies indicating that moisture levels around 70% can accelerate the heating rate and enhance microbial interactions, leading to improved humification and nutrient availability (Sun et al., 2024). Furthermore, moisture influences the grinding ratio of raw materials, which correlates negatively with C/N and total organic carbon, affecting overall compost quality (Wang et al., 2018).

The influence of composting moisture levels on N mineralization and ammonia volatilization is significant, with varying effects observed at 65 and 80% moisture content, respectively. At 65% moisture, composting demonstrated a 33.3% increase in total N content and reduced gaseous emissions, including ammonia, by 100% during the late mesophilic phase. Conversely, higher moisture levels (80%) were associated with increased ammonia volatilization, particularly when urea was applied, as evidenced by the highest ammonia (NH_3) fluxes recorded at 50% water-filled pore space (Castellano-Hinojosa et al., 2019). Additionally, moisture content impacts the kinetic and thermodynamic parameters of ammonia volatilization, with interactions between moisture and temperature significantly affecting reaction rates (Tao et al., 2017).

CONCLUSION

This study assessed the use of BSFL for frassing food waste at two different moisture levels (65 and 80%). The findings underscore the critical role of moisture content in influencing the compost's physical, chemical, and nutrient properties. While both moisture levels produced similar physical outcomes, the 80% treatment retained more moisture, highlighting the need for moisture control in optimizing composting processes. The 80% moisture level also showed higher nutrient solubility and microbial activity, whereas the 65% moisture treatment demonstrated more efficient organic matter decomposition. Both moisture treatments produced nutrient-rich frass, with the 65% treatment showing slightly higher retention of N and C, which are important for agricultural use. The study also found no significant nutrient loss between treatments, confirming that BSFL composting is effective in minimizing nutrient leaching. Overall, BSFL composting offers a sustainable alternative to traditional waste management practices, providing high-quality organic fertilizers and contributing to food waste diversion. In conclusion, optimizing moisture content in BSFL composting improves compost quality and nutrient recovery, with the 65% treatment being more efficient in organic matter decomposition and nutrient retention. These insights are useful for scaling up BSFL composting systems, especially in areas with food waste management challenges. Future research should focus on the long-term effects of BSFL compost on soil health and crop productivity to further establish this method as a sustainable solution for food waste management and environmental sustainability.

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