JURNAL ILMU LINGKUNGAN
Volume 23 Issue 5 (2025) : 1412-1422 ISSN 1829-8907

Black Soldier Fly Larval Bioconversion of Fruit and Vegetable Waste: Carbon-Nitrogen Conversion and Estimation of Greenhouse Gas Emissions

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ABSTRAK

Sampah buah dan sayur menyumbang sekitar 36% dari total sampah makanan di Indonesia. Akumulasi sampah ini di tempat pemrosesan akhir (TPA) berkontribusi terhadap peningkatan emisi gas rumah kaca (GRK) serta pencemaran lingkungan akibat produksi lindi. Pengolahan menggunakan larva *Black Soldier Fly* (BSF) menawarkan alternatif yang efisien dan berkelanjutan, dengan emisi GRK yang lebih rendah dibandingkan metode komposting maupun digesti anaerobik. Penelitian ini bertujuan untuk mengevaluasi efisiensi biokonversi larva BSF dalam mengurangi sampah buah dan sayur (yakni kol, kangkung, bayam, sawi, semangka, melon, pisang, dan pepaya) melalui analisis transformasi karbon (C) dan nitrogen (N) menjadi biomassa larva dan residu. Komposisi substrat divariasikan dengan rasio sayur terhadap buah sebesar 90:10, 80:20, 70:30, dan 60:40 (b/b), serta diuji pada kepadatan larva 1, 2, dan 4 larva/cm^2. Hasil menunjukkan bahwa konversi karbon dan nitrogen menjadi biomassa larva masing-masing berkisar antara 7,92–17,59% dan 4,96–21,69%, sedangkan konversi ke residu berkisar antara 22,53–63,75% untuk karbon dan 18,12–80,78% untuk nitrogen. Substrat dengan rasio sayur: buah 90:10 menghasilkan efisiensi konversi tertinggi. Nilai *Approximate Digestibility* (AD), *Efficiency of Conversion of Digested Food* (ECD), dan *Efficiency of Conversion of Ingested Food* (ECI) masing-masing berada pada kisaran 32,44–74,71%, 17,68–42,96%, dan 8,09–18,64%. Tingkat kelangsungan hidup larva mencapai 95,61%. Selain itu, biokonversi dengan larva BSF menghasilkan emisi GRK terendah di antara semua metode pengolahan sampah yang dibandingkan, yaitu sebesar 102,27 g CO_2 ek/kg sampah. Temuan ini menunjukkan potensi signifikan larva BSF dalam pengelolaan sampah buah dan sayur sekaligus meminimalkan dampak lingkungan, serta menjadi dasar bagi optimalisasi lebih lanjut dalam sistem pemanfaatan sampah yang berkelanjutan.

***Kata kunci*:** Karbon, Nitrogen, Larva black soldier fly, Kepadatan larva, Biokonversi

ABSTRACT

Fruit and vegetable waste accounts for approximately 36% of total food waste in Indonesia. The accumulation of this waste in landfills contributes to increasing greenhouse gas (GHG) emissions and environmental pollution through leachate production. Treatment using Black Soldier Fly (BSF) larvae offers an efficient and sustainable alternative, with lower GHG emissions compared to composting or anaerobic digestion. This study aimed to evaluate the bioconversion efficiency of BSF larvae in reducing fruit and vegetable waste (specifically cabbage, water spinach, spinach, mustard greens, watermelon, melon, banana, and papaya) by analyzing the transformation of carbon (C) and nitrogen (N) into larval biomass and residue. Substrate compositions were varied with vegetable-to-fruit ratios of 90:10, 80:20, 70:30, and 60:40 (w/w), and larval densities of 1, 2, and 4 larvae/cm^2 were tested. Results showed that carbon and nitrogen conversion into larval biomass ranged from 7.92–17.59% and 4.96–21.69%, respectively, while conversion into residue ranged from 22.53–63.75% for carbon and 18.12–80.78% for nitrogen. The substrate with a 90:10 vegetable-to-fruit ratio produced the highest conversion efficiency. The values of Approximate Digestibility (AD), Efficiency of Conversion of Digested Food (ECD), and Efficiency of Conversion of Ingested Food (ECI) ranged from 32.44–74.71%, 17.68–42.96%, and 8.09–18.64%, respectively. The larval survival rates reached 95.61%. Furthermore, BSF bioconversion generated the lowest GHG emissions among all compared waste treatment methods, with a value of 102.27 g CO_2 eq/kg of waste. These findings demonstrate the significant potential of BSF larvae in managing fruit and vegetable waste while minimizing environmental impact, providing a foundation for further optimization in sustainable waste valorization systems.

***Keywords*:** Carbon, Nitrogen, Black soldier fly larvae, Larval density, Bioconversion

Citation: Ursada, R., Zuhdi, A., Bagastyo, A. Y., Febrianto, A. (2025). Black Soldier Fly Larval Bioconversion of Fruit and Vegetable Waste: Carbon-Nitrogen Conversion and Estimation of Greenhouse Gas Emissions. Jurnal Ilmu Lingkungan, 23(5), 1412-1422, doi:10.14710/jil.23.5.1412-1422

1. INTRODUCTION

Indonesia, with a population of approximately 270 million, generated an estimated 31 million tons of municipal solid waste in 2023, of which 40.6% was food waste (Kementerian Lingkungan Hidup dan Kehutanan Sistem Informasi Pengelolaan Sampah Nasional, 2024). Fruit and vegetable waste are the largest contributors to food waste in the country, accounting for 16% and 20%, respectively (Kementerian Perencanaan Pembangunan Nasional, 2021). A significant portion of this organic waste is directly disposed of in landfills, resulting in environmental pollution, greenhouse gas (GHG) emissions, and a shortened landfill lifespan (Akbar, 2016; Lutviyani et al., 2022; Puger, 2018). Conventional treatment methods such as composting and anaerobic digestion also produce considerable GHG emissions, highlighting the need for more efficient and sustainable waste management alternatives.

An emerging method for managing fruit and vegetable waste is bioconversion using *Hermetia illucens* (Black Soldier Fly, BSF) larvae. These larvae can efficiently consume organic waste and convert it into valuable biomass. BSF larval bioconversion offers several advantages, including lower GHG emissions compared to composting and anaerobic digestion. In fact, total GHG emissions from BSF-based treatment have been reported to be up to 90% lower than those from composting processes (Ermolaev et al., 2019; Mertenat et al., 2019; Pang, Hou, Chen, et al., 2020).

Understanding the factors that influence the efficiency of BSF larval bioconversion is essential to support the development of waste treatment technologies using this method. Bioconversion efficiency can be evaluated based on the larvae's ability to reduce substrate volume and generate larval biomass during the treatment process. Additionally, the conversion of carbon (C) and nitrogen (N) into larval biomass, as well as the losses of C and N throughout bioconversion, serve as key indicators of process performance. The higher the proportion of C and N converted into larval biomass, the more efficient the bioconversion process.

Previous studies have shown that BSF larvae can convert approximately 27–35.5% of carbon and 63.5–75% of nitrogen from food waste with a C/N ratio ranging from 21 to 10 (Jin et al., 2022). A mixture of food waste and straw with a high C/N ratio of 127.3 resulted in carbon and nitrogen conversion into larval biomass ranging from 1.95–13.41% and 5.4–18.93%, respectively (Pang, Hou, Chen, et al., 2020). Meanwhile, bioconversion of a mixture of pig manure and corn stalks with a C/N ratio between 35 and 15 yielded carbon conversion of 4.17–6.61% and nitrogen conversion of 17.45–23.73% (Pang, Hou, Nowar, et al., 2020).

Larval density—defined as the number of larvae per unit surface area—is another critical factor influencing BSF bioconversion efficiency. Larval density plays a significant role in determining the larvae's ability to reduce organic substrate (Purnomo et al., 2021). For optimal larval biomass production, an ideal density is typically within the range of 1.2–5 larvae/cm^2, with a feeding rate not exceeding 95 mg/larva/day. Excessively high densities may hinder larval movement and increase competition for the substrate, while overly low densities may result in suboptimal substrate consumption and reduced conversion efficiency (Purnomo et al., 2021). Therefore, this study aims to evaluate the carbon and nitrogen conversion in BSF larval bioconversion of fruit and vegetable waste using various substrate compositions and larval densities.

2. METHODS & MATERIALS

2.1. Preliminary Research

Preliminary analysis was performed to determine moisture, organic carbon, and nitrogen (organic and inorganic) contents of fruit and vegetable waste used as BSF larvae feed. Waste was collected from temporary storage sites near traditional markets or directly from vendors in Surabaya, then sorted, bagged, and transported to the research site. The selected fruit and vegetable waste, categorized as food loss, consisted of relatively fresh, minimally decayed organic materials such as leaves, stems, peels, flesh, and seeds. Vegetable waste included cabbage, water spinach (*Ipomoea aquatica*), spinach (*Amaranthus* spp.), and mustard greens (*Brassica juncea*), while fruit waste comprised watermelon, melon, banana, and papaya. This selection of fruit and vegetable types was based on their frequent and consistent occurrence as waste in traditional markets, ensuring a steady and representative supply of organic material for BSF feeding.

Table 1. Research Variable

Substrate composition (%)	Larval density (larvae/cm^2)	Code	Feeding rate (mg/larvae/day
Vegetable (100)	1	A1	35
	2	A2	
	4	A4	
Vegetable : Fruit (90:10)	1	B1	
	2	B2	
	4	B4	
Vegetable : Fruit (80:20)	1	C1	
	2	C2	
	4	C4	
Vegetable : Fruit (70:30)	1	D1	
	2	D2	
	4	D4	
Vegetable : Fruit (60:40)	1	E1	
	2	E2	
	4	E4	

After collecting, the fruit and vegetable waste was shredded until it reached a slurry-like consistency. It was then portioned according to the substrate compositions listed in Table 1. The prepared waste was stored in sealed containers at a temperature of approximately 4°C in the cold storage to maintain freshness prior to use in the bioconversion experiments.

2.2. Black Soldier Fly Larval Rearing

BSF larval rearing was conducted over two different durations, namely 8 days and 12 days, at the BSF Larvae Facility of the Environmental Engineering Department, Institut Teknologi Sepuluh Nopember. The rearing durations of 8 and 12 days were determined to evaluate the progression of substrate conversion across different larval developmental phases. The 8-day duration was selected because larvae at this age exhibited sufficient size to meet sampling requirements without substantially reducing the total larval population. In contrast, the 12-day duration was chosen as it represented the stage when a portion of the larvae had begun to transform into prepupae. Five-day-old larvae (5 days after oviposition, or 5 DOL) were used as the initial stock and obtained from the Wonorejo Composting Center in Surabaya.

The substrates, prepared according to the designated composition variables, were weighed and applied based on a feeding rate of 35 mg/larva/day. The feeding rate was adopted based on a previous study, which reported that this rate resulted in the highest food waste bioconversion efficiency and the lowest residue generation when using BSF larvae (Hartono et al., 2021). Feeding was carried out every two days throughout the rearing period. Feeding was conducted every two days to prevent prolonged substrate retention in the reactor and to allow timely addition of fresh substrate, while also accommodating the preparation process such as waste collection and shredding.

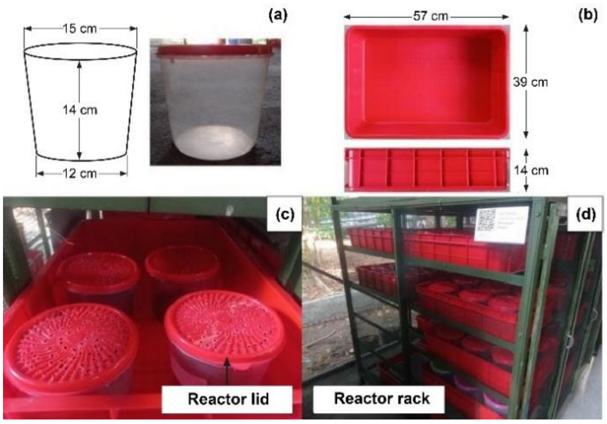

Figure 1. BSF Larval Rearing Reactors

The BSF larval rearing reactors were cylindrical plastic containers with a top diameter of 15 cm, bottom diameter of 12 cm, and height of 14 cm. A total of 15 reactors were used in this study without replication. Each reactor contained a different substrate mixture as presented in Table 1. These reactors were placed inside rectangular plastic trays measuring 59 cm in length, 39 cm in width, and 14 cm in height. Each tray held six individual rearing reactors. The reactors were covered with lids and placed on designated racks to prevent larval escape, as illustrated in Figure 1.

At the end of the rearing period, samples of BSF larvae and residual substrate were collected. Separation was performed using a sieve, allowing the larvae to crawl through the mesh and fall into a collection container below, while the residual substrate remained on the sieve. The separated BSF larvae and residual substrate were then collected in zip-lock bags. The harvested larvae were rinsed with water to remove dirt and debris, then gently dried with tissue paper. The cleaned samples were stored in a refrigerator or freezer at approximately 4°C, prior to further analysis.

2.3. Analysis

The moisture content was determined using the oven method according to SNI 01-2891-1992. Organic carbon (C) content was determined using the gravimetric method (Adams et al., 1951). Nitrogen content was analyzed by measuring Total Kjeldahl Nitrogen (TKN) according to EPA-NERL: 351.3, which provides values for both organic nitrogen and ammonia (EPA, 1978). Additionally, spectrophotometric analysis was performed to determine the concentrations of nitrate and nitrite according to EPA-NERL: 351.3 (EPA, 1978).

The relationship between food conversion efficiency and the capacity for carbon (C) and nitrogen (N) conversion during the bioconversion process was analyzed. This analysis allowed for an understanding of how variation in substrate composition and larval density affects the overall efficiency of the BSF bioconversion process in terms of C and N utilization. Waste reduction index (WRI), survival rate (SR), and food conversion efficiencies, including efficiency conversion of ingested food (ECI), approximate digestibility (AD), and efficiency conversion of digested food (ECD), were also calculated. The calculation formulas can be seen in Equations 1 to 7 (Meneguz et al., 2018; Permana & Putra, 2018; Waldbauer, 1968).

$$\text{C conversion (\%)} = \frac{\text{C mass adult larvae}}{\text{C mass total substrate}} \text{x } 100 \quad (1)$$

$$\text{N conversion (\%)} = \frac{\text{N mass adult larvae}}{\text{N mass total substrate}} \text{x } 100 \quad (2)$$

$$\text{AD (\%)} = \frac{\text{total substrate } (g) - \text{residue } (g)}{\text{total substrate } (g)} \text{x } 100 \quad (3)$$

$$\text{WRI (\%)} = \frac{\frac{\text{total substrate } (g) - \text{residue } (g)}{\text{total substrate } (g)}}{\text{days of trial } (d)} \text{x } 100 \quad (4)$$

$$\text{ECD (\%)} = \frac{\text{larvae weight } (g)}{\text{total substrate } (g) - \text{residue } (g)} \text{x } 100 \quad (5)$$

$$\text{ECI (\%)} = \text{ECD x AD x } 100 \quad (6)$$

$$\text{SR (\%)} = \frac{\text{final number of live larvae}}{\text{initial number of live larvae}} \text{x } 100 \quad (7)$$

GHG emissions were estimated by calculating the losses of carbon and nitrogen (as nitrate and nitrite) during the BSF larval bioconversion process. These losses were expressed in terms of atomic weight of carbon and nitrogen, then converted to GHG emissions using the ratio of atomic weight to molecular weight of the respective gases. Carbon loss was used to estimate emissions of CO_2 and CH_4, while nitrate and nitrite losses were used to estimate N_2O emissions. The ratio of CO_2 to CH_4 emissions applied was 39,416.06:1, based on a study that used fruit and vegetable waste as substrate (Komakech et al., 2023). The estimated GHG emissions from BSF bioconversion were then compared with those from composting, anaerobic digestion, and landfilling, using GHG emission factors that were reported (EPA, 2024; IPCC, 2006; Komakech et al., 2023).

3. RESULTS AND DISCUSSION

3.1. Substrate Characteristics

As shown in Table 2, the moisture content of the feed substrate ranged from 87.73% to 89.56%, which is within the optimal range for BSF larval growth. BSF larvae can thrive on substrates with moisture content ranging from 70% to 90% (Cheng et al., 2017; Salam et al., 2022). Additionally, the carbon-to-nitrogen (C/N) ratio of the feed substrate ranged from 14 to 20, which is considered ideal for both substrate reduction and BSF larval growth (Beesigamukama et al., 2021; Jin et al., 2022; Lu et al., 2021).

Table 2. Substrate Characteristics

Measurand	Substrate composition				
	A	B	C	D	E
Moisture content (%)	87.73	88.34	88.95	89.23	89.56
Ash (%)	11.28	10.59	10.19	9.56	9.06
Carbon (%)	51.58	51.98	52.22	52.58	52.87
Nitrogen (%)	3.45	3.17	3.05	2.85	2.62
C/N ratio (%)	14.93	16.4	17.11	18.44	20.21

The moisture content, carbon content, and C/N ratio of the substrate compositions increased with a higher proportion of fruit in the substrate. This is because fruit mixtures typically have higher moisture content compared to vegetable mixtures, and fruits contain higher levels of sugar, contributing to a greater carbon content than the vegetable mixtures. Conversely, the ash and nitrogen contents increased in substrates with a higher proportion of vegetables, as vegetable mixtures tend to have higher nitrogen content (Saputra & Nuryanti, 2018; U.S. Department of Agriculture, 2024).

3.2. Carbon and Nitrogen Content in BSF Larvae

As shown in Figure 2, the carbon content in BSF larvae from the rearing experiments ranged from 46.75% to 50.63%. The lowest carbon content was observed in the larvae reared on A1 over 12 days, while the highest carbon content was found in the larvae reared on E4 over 8 days. The carbon content values in this study are comparable to those found in previous studies, which reported carbon content values of 47.61% and 51.56% for vegetable and fruit substrates, and 47.83% for a mixed vegetable and fruit substrate (Andari et al., 2021; Barrera et al., 2023). The carbon content in BSF larvae increased with both higher larval density and the addition of more fruit in the substrate.

The elevated carbon content may be attributed to the higher fat content in the larvae. Excess carbohydrates in the diet are converted into fats through the larvae's metabolic processes (Carpentier et al., 2024). Increased larval density has been shown to elevate the fat content in BSF larvae (Barragan-Fonseca et al., 2018). Additionally, the high fructose content in fruits, a simple sugar, also contributed to the higher carbon content in the larvae. The presence of sugars in the larvae feed facilitates the larvae's ability to obtain carbohydrates as a carbon source (Agustin et al., 2023; Prahastuti, 2011).

As shown in Figure 3, the nitrogen content in BSF larvae ranged from 1.26% to 4.29%. The lowest nitrogen content was observed in larvae reared on B1 over 12 days, while the highest nitrogen content was found in larvae reared on A2 over 8 days. The nitrogen content in the BSF larvae from this study was lower than values reported in previous research, which showed nitrogen content ranging from 5% to 7% when reared on pig manure substrates, 7% on a wheat and starch powder substrate, and 6.1% to 7.1% on food waste substrates (Jin et al., 2022; Parodi et al., 2020, 2022).

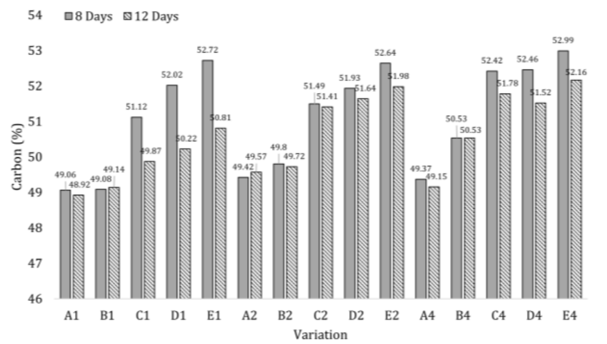

Figure 2. Carbon Content of BSF Larvae

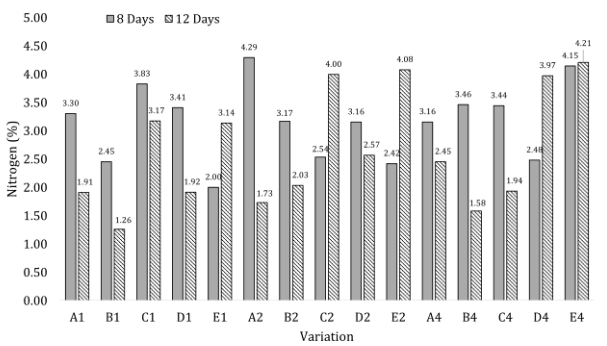

Figure 3. Nitrogen Content of BSF Larvae

The higher organic-carbon and nitrogen contents observed in larvae harvested at 8 days compared with 12 days may be attributed to the larval developmental stage and associated metabolic changes. Younger larvae (8 days) are still actively feeding and accumulating biomass, resulting in relatively higher protein (and hence nitrogen) content and higher metabolically stored carbon (e.g., lipids). In contrast, by 12 days many larvae may have begun transitioning into the prepupal phase, during which feeding declines or ceases (Liu et al., 2017).

The lower nitrogen content in the BSF larvae from this study may be due to the low protein content in the substrates, as well as the high fiber content. Low protein levels in the larval feed during rearing can result in reduced nitrogen content in the larvae (Aldis et al., 2024). Furthermore, fiber is indigestible to BSF larvae, and high fiber content in the feed can reduce the overall nutrient density available for larval growth, resulting in lower nitrogen content in the larvae (Froonickx et al., 2023; Gold et al., 2018).

3.3. Carbon and Nitrogen Content in Residues

As shown in Figure 4, the carbon content in the residues ranged from 42.76% to 47.89% for the 8-day and 12-day rearing periods. The lowest carbon content in the residues was observed in A1 after 12 days of rearing, while the highest carbon content was found in B2 after 12 days of rearing. A higher carbon weight in the residue leads to a higher conversion of carbon into residues, while a lower carbon weight results in a lower conversion of carbon into residue. There was a decrease in carbon content in the substrate after it was consumed by the BSF larvae, indicating that some of the carbon was converted into biomass by the larvae. Additionally, the carbon content in the residues tended to be lower at a larval density of 1 larva/cm^2, suggesting that more carbon was converted into BSF biomass and/or lost at lower larval densities. The carbon content in the residues of this study was comparable to values obtained in previous studies, which reported carbon content in residues of 41.40% to 50.14% for mixed vegetable and fruit waste substrates (Oemar et al., 2023).

The higher carbon content observed in the residues on day 12 at larval densities of 2 and 4 larvae/cm^2 is likely related to the developmental stage of the BSF larvae. Around day 12, many larvae begin transitioning from the active feeding phase to the pre-pupal stage, during which feeding activity declines or ceases (Liu et al., 2017). As a result, less substrate is consumed and metabolized, leaving a greater proportion of unutilized organic matter in the residue. This remaining fraction, which is rich in carbon-based compounds such as cellulose, lignin, and lipids, contributes to the higher measured carbon content in the residues. Although microorganisms also metabolize carbon during degradation, the residual substrate at day 12 likely contained more recalcitrant carbon compounds (e.g., lignin and cellulose) that are less readily degraded (Diener et al., 2011; Lalander et al., 2019).

As shown in Figure 5, the nitrogen content in the residues ranged from 1.67% to 4.48%. The lowest nitrogen content in the residues was observed in C2 after 12 days of rearing, while the highest nitrogen content in the residues was found in A1 after 8 days of rearing. The nitrogen content in the residues from this study was similar to previous research on mixed vegetable and fruit waste residues, which ranged from 1.303% to 3.701% (Oemar et al., 2023).

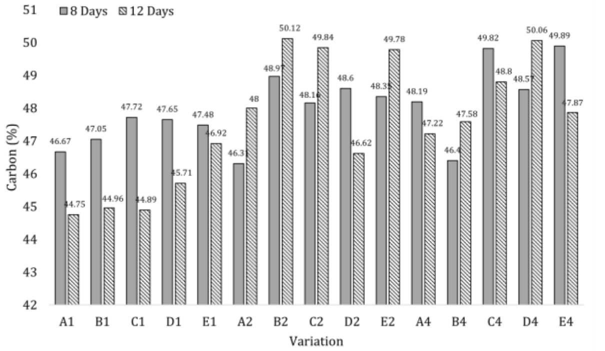

Figure 4. Carbon Content of Residue

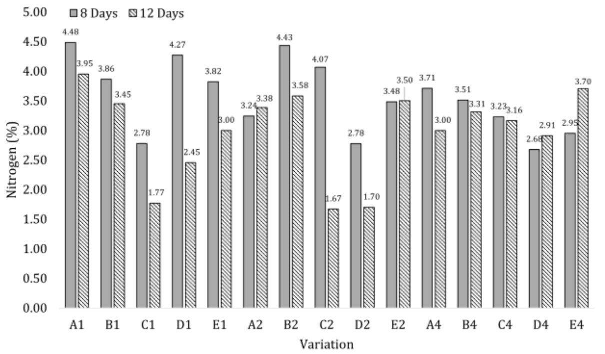

Figure 5. Nitrogen Content of Residue

An increase in nitrogen content in the residues, compared to the initial nitrogen content of the substrate, may be due to the decomposition of organic matter and nitrogen mineralization by microorganisms, which produces nitrogen. Additionally, the biochemical activity in the BSF larvae's digestive system contributes to the nitrogen present in the residues (L. Purnamasari et al., 2021; Sarpong et al., 2019).

3.4. Carbon and Nitrogen Conversion

The percentage of carbon converted into BSF larva biomass during the 8-day and 12-day rearing periods ranged from 10.52% to 17.59% and 7.92% to 13.76%, respectively. In contrast to previous studies using food waste, which reported carbon conversion rates ranging from 27% to 35.5% (Jin et al., 2022). Bioconversion of food waste and straw mixtures yields carbon conversion from 1.95% to 13.41% (Pang, Hou, Chen, et al., 2020). In the bioconversion of pig manure and corn stalk mixtures, the carbon conversion rate to BSF larva biomass ranges from 4.17% to 6.61% (Pang, Hou, Nowar, et al., 2020). The carbon conversion into BSF larva biomass was higher during the 8-day rearing period compared to the 12-day period because the larvae in the 12-day rearing had entered the pre-pupal phase, during which they consume little or no food and mostly move around seeking shaded, dry, and safe areas to pupate (Dortmans et al., 2021; Lievens et al., 2021; Putra & Ariesmayana, 2020; Wardhana, 2017).

As shown in Figures 6 and 7, the rearing of BSF larvae at a density of 1 larva/cm^2 was more efficient in converting carbon into larval biomass, but the carbon converted into residue was low. This could be attributed to the low density, which allows the larvae to move more freely, causing more carbon as an energy source to be wasted (Parodi et al., 2022; Parra Paz et al., 2015a).

According to Figures 8 and 9, the percentage of nitrogen converted into BSF larva biomass during the 8-day and 12-day rearing periods ranged from 9.21% to 19.95% and 4.96% to 21.69%, respectively. The percentage of nitrogen converted into residue during the 8-day and 12-day rearing periods ranged from 30.68% to 80.78% and 18.12% to 62.82%, respectively. The nitrogen conversion into BSF larva biomass in this study differed from studies using vegetable and fruit waste substrates (Lalander et al., 2019) and food waste substrates (Jin et al., 2022), where nitrogen conversion into larval biomass was reported to be 34.3% and 35% to 75%, respectively. However, the nitrogen conversion values in this study were similar to those observed in studies using food waste and straw mixtures (Pang, Hou, Chen, et al., 2020) and pig manure and corn stalk mixtures (Purnomo et al., 2021), where nitrogen conversion into larva biomass ranged from 5.4% to 18.93% and 17.45% to 23.73%, respectively.

The high fiber content in the substrate may have caused the lower nitrogen conversion in the BSF larvae because the larvae are unable to digest fiber, and the high fiber content in the substrate could reduce the overall nutritional density for larval growth (Froonickx et al., 2023; Gold et al., 2018). The higher nitrogen content in the residues compared to both the initial substrate and larval biomass can be attributed to microbial decomposition and nitrogen mineralization processes that generate or retain nitrogen within the substrate. Biochemical activity in the BSF larvae's digestive system may also contribute to nitrogen compounds remaining in the residue (L. Purnamasari et al., 2021; Sarpong et al., 2019). However, BSF larvae assimilate only a fraction of the available nitrogen into their tissues, while a considerable portion stay bound within the residual substrate or microbial biomass and may also be lost through gaseous emissions such as ammonia (NH_3) or nitrous oxide (N_2O) during decomposition (Parodi et al., 2020). As a result, more nitrogen tends to remain in the residue than is incorporated into larval biomass.

In this study, the relationship between the carbon and nitrogen contents in BSF larvae and residues was not always inversely related. This is because part of the substrate carbon and nitrogen remains in the residue, part is assimilated into larval biomass, and another portion is lost as gaseous emissions such as CO_2 and NH_3 during decomposition and metabolism (Eriksen, 2024; Parodi et al., 2020). The efficiency of feed conversion by BSF larvae depends not only on the match between substrate composition and larval nutritional needs but also on the complex interactions among larvae, microbes, and the physical and chemical environment (Eriksen, 2024). These interactions affect how much of the substrate's carbon and nitrogen are incorporated into larvae, retained in residues, or released as gases. Therefore, while a high larval carbon content could theoretically correspond to a lower carbon content in the residue under efficient conversion, this pattern is not always observed in practice due to variations in substrate degradation, microbial respiration, and nutrient assimilation efficiency.

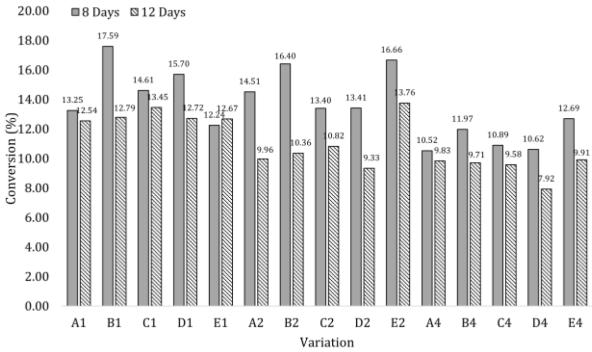

Figure 6. Conversion of Substrate Carbon to BSF Larvae Carbon

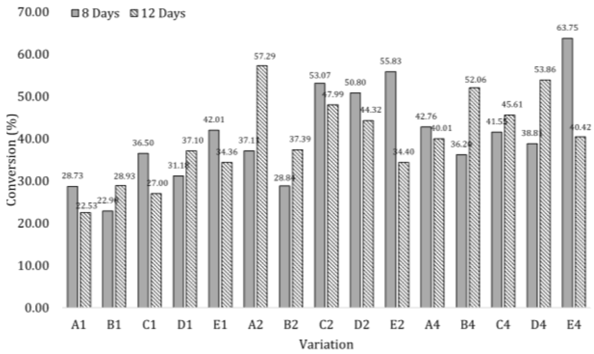

Figure 7. Conversion of Substrate Carbon to BSF Residue Carbon

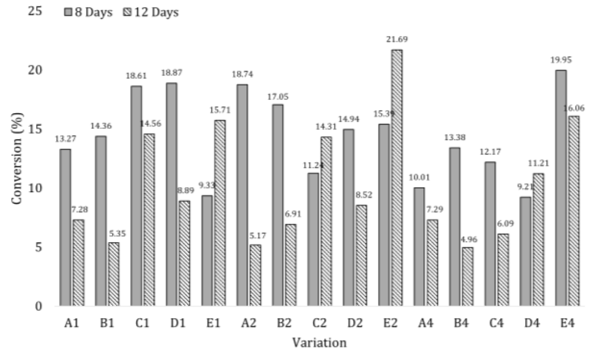

Figure 8. Conversion of Substrate Nitrogen to BSF Larvae Nitrogen

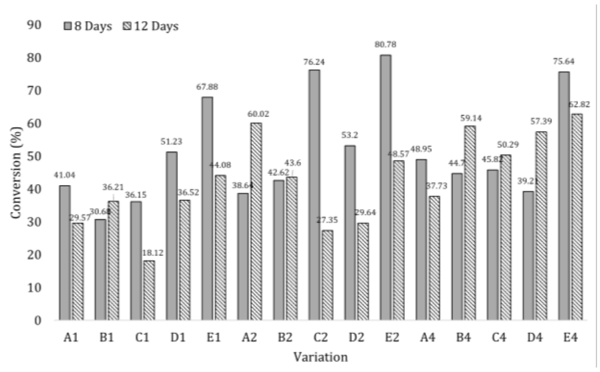

Figure 9. Conversion of Substrate Nitrogen to Residue Nitrogen

3.5. Larval Moisture Content

No significant differences in moisture content were observed across the variations in larval density and substrate composition. The moisture content of BSF larvae reared for 8 days ranged from 67.68% to 70.97%. The lowest moisture content was found in variation D2, while the highest was observed in variation B1. For larvae reared over 12 days, moisture content ranged from 62.27% to 65.66%, with the lowest value in variation C2, and the highest in variation A1.

The BSF larvae moisture content in this study, ranging from 67.68–70.97% (8-day rearing) and 62.27–65.66% (12-day rearing), is similar to the range reported by previous studies using fruit and vegetable substrates, such as 63.37–67.41% (Saragi, 2015). However, these values are relatively lower compared to the findings of other studies, which reported moisture contents of 78.90% using vegetable substrates (Amri et al., 2023) and 78.90–81.95% using fruit and vegetable substrates (D. K. Purnamasari et al., 2023). Lower moisture content in BSF larvae may indicate a higher fat content, as suggested by (Amri et al., 2023). The decline in moisture content from day 8 to day 12 is associated with the physiological transition of the larvae into the prepupal stage, during which water content typically decreases (D. K. Purnamasari et al., 2023).

3.6. Bioconversion Performance

Substrate reduction was calculated based on the dry weight of the initial feed and resulting residue to assess the consumption efficiency of BSF larvae (Meneguz et al., 2018). After 8 days of rearing, substrate reduction ranged from 32.44% to 74.71%, with the highest reduction observed in B1 and the lowest in E4. For the 12-day rearing period, reduction ranged from 38.44% to 74.03%, with the highest in A1 (68.25%) and B1 (66.55%). Overall, lower larval density resulted in higher substrate reduction due to improved feed accessibility (Parra Paz et al., 2015b). Substrates with higher vegetable content also showed greater reduction compared to fruit-dominant ones (Amin et al., 2024; Triwandani et al., 2023). This is likely because vegetable wastes generally contain lower fiber, higher moisture, and a more balanced nutrient composition, making them easier to degrade and more readily consumed by BSF larvae. In contrast, fruit wastes typically contain higher levels of simple sugars and organic acids, which may rapidly ferment and inhibit larval feeding activity. Substrates with favorable physical properties and moderate moisture content, such as vegetable residues, enhance larval activity and bioconversion efficiency (Meneguz et al., 2018). Additionally, substrate reduction decreased in the 12-day rearing due to reduced feed intake by larvae entering the prepupal stage (Dortmans et al., 2021; Lievens et al., 2021; Putra & Ariesmayana, 2020). The waste reduction index ranged from 4 to 9.4% dry matter.

Approximate Digestibility (AD) is defined as the proportion of feed that is digested relative to the total amount provided (Permana & Putra, 2018; Waldbauer, 1968). The AD values observed in the 12-day rearing period were consistently lower than those recorded at 8 days as can be seen on Figure 10. This decline is likely due to a reduction in larval feeding activity, as many individuals had entered the prepupal stage by day 12, where feeding is known to diminish (Dortmans et al., 2021; Lievens et al., 2021; Putra & Ariesmayana, 2020). The highest AD was recorded in substrate composition B1. Lower larval densities generally resulted in higher AD values, likely due to reduced competition and better feed accessibility (Parra Paz et al., 2015b). Conversely, higher densities and low survival rates may have led to uneaten feed, reducing overall digestibility. Compared to previous findings, the AD values in this study were lower than the BSF larvae fed kitchen waste values 87.7% (Mahmood et al., 2021).

Efficiency of Conversion of Digested Food (ECD) represents the larvae's ability to transform digested feed into body mass. Higher ECD values indicate more efficient bioconversion processes (Permana & Putra, 2018; Waldbauer, 1968). Figure 11 shown ECD values, the highest ECD during the 8-day rearing was achieved with substrate composition E2. In the 12-day rearing, the highest ECD (26.97%) was recorded in substrate A2. These findings align with ECD values between 11–56% using fruit and vegetable substrates (Rofi et al., 2021). Notably, ECD values in this study were generally higher than BSF reared on kitchen waste and coffee waste values 16.60% and 2.71–5.00% respectively (Mahmood et al., 2021; Permana & Putra, 2018), suggesting favorable conversion efficiency under the tested conditions.

At day 8, reactors E2 and E4 showed unusually high Efficiency of Conversion of Digested food (ECD) values compared to day 12 and the other treatments. Since the moisture content of substrate, residue, and larvae among all reactors was relatively similar, this difference was not likely caused by water loss. The higher ECD values might be attributed to the relatively lower food consumption measured in E2 and E4 at day 8, while larval biomass gain remained comparable to other reactors. This condition resulted in a higher ratio of biomass gain to food digested. It is possible that larvae in these reactors selectively consumed more nutrient-dense fractions of the substrate, leading to temporarily higher assimilation efficiency. In addition, larvae might have been at a developmental stage that allowed more efficient nutrient utilization. Alternatively, the discrepancy could be related to slight underestimation of the digested substrate due to sampling or measurement variations. As the ECD values converged by day 12, this transient peak is interpreted as a short-term fluctuation rather than a sustained improvement in conversion efficiency.

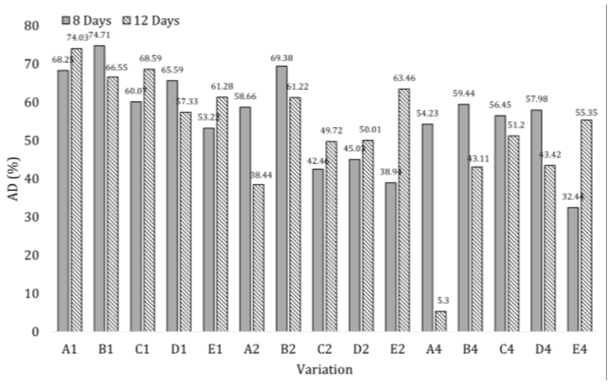

Figure 10. Approximate Digestibility

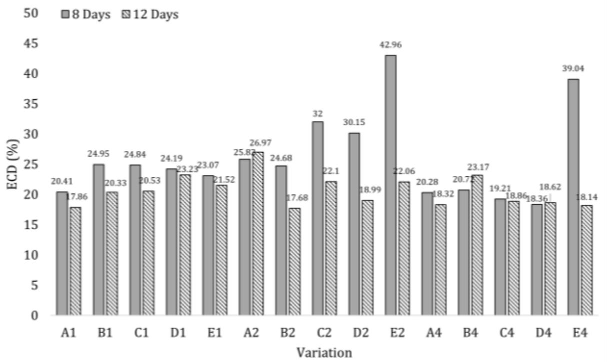

Figure 11. Efficiency of Conversion of Digested Food

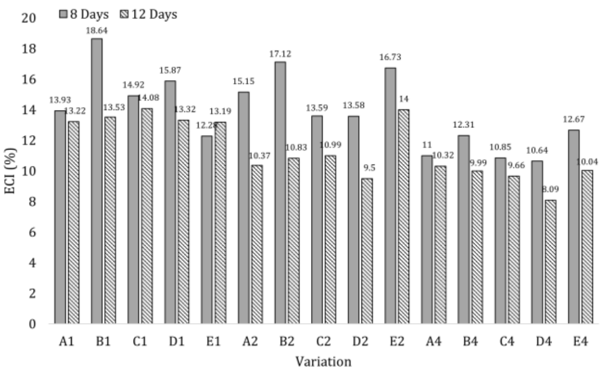

Figure 12. Efficiency of Conversion of Ingested Food

Efficiency of Conversion of Ingested Food (ECI) measures the proportion of ingested feed that is utilized for energy production and biomass formation. It is influenced by feed digestibility and the larvae's metabolic efficiency (Permana & Putra, 2018; Waldbauer, 1968). ECI values can be seen on Figure 12. The highest value was observed in substrate B1, while the lowest was found in substrate D4. At this stage, ECI values for larval densities of 1, 2, and 4 larvae/cm^2 ranged from 12.28–18.64%, 13.58–17.12%, and 10.64–16.73%, respectively. For the 12-day rearing, highest ECI values is observed in substrate C1. The trend showed that lower larval densities generally supported higher ECI values. High ECI reflects efficient conversion of ingested feed into larval biomass and energy, highlighting the importance of optimizing both substrate composition and rearing conditions.

Collectively, these results emphasize the significance of larval density and substrate composition in influencing BSF larvae's feeding performance. Optimal combinations of vegetable-rich substrates and lower larval densities consistently supported improved digestibility and conversion efficiencies, offering valuable insights for enhancing the sustainability and productivity of BSF bioconversion system. Table 3 presents the characteristics of larvae, prepupae, and residues from reactor B1, which was identified as the most effective treatment in terms of bioconversion performance, including waste reduction, efficiency of conversion of ingested food, and approximate digestibility.

Table 3. Larvae, Prepupae, and Residue Characteristics

Measurand	Larvae	Prepupae	Residue
Moisture content (%)	70.79	64.92	92.66
Ash (%)	15.59	15.49	22.67
Carbon (%)	49.08	49.14	44.96
Nitrat (%)	0.0015	0.014	0.007
Nitrit (%)	0.007	0.004	0.004
N organic (%)	2.432	1.242	3.438

3.7. Estimates of GHG emissions

The carbon and nitrogen losses during the BSF larval bioconversion process are primarily released in gaseous forms. Carbon is emitted as carbon dioxide (CO_2) and methane (CH_4), generated through larval metabolism, respiration, and substrate decomposition processes. Meanwhile, nitrogen is lost as ammonia (NH_3) and nitrous oxide (N_2O). NH_3 is released through volatilization of organic nitrogen, while N_2O is formed via nitrification and denitrification of nitrite and nitrate compounds (Froonickx et al., 2023).

The estimated GHG emissions include CO_2, CH_4, and N_2O, while NH_3 was not considered due to its exclusion as a greenhouse gas. According to the emission estimates presented in Table 4, BSF bioconversion generated the lowest GHG emissions among all compared waste treatment methods, with a value of 102.27 g CO_2 eq/kg of waste. These findings suggest that BSF larval bioconversion is a more environmentally friendly approach for processing fruit and vegetable waste when compared to composting, anaerobic digestion, and landfilling.

Table 4. Estimates of GHG Emissions

Processing Method (Emission Factor Source)	Total Emission (g CO2 eq)				
	CO_2	CH_4	N_2O	Total	Emisi (g CO_2 eq/kg waste)
Bioconversion of BSF Larvae	2429.41	0.56	120.65	2550.62	102.27
Composting (Komakech et al., 2023)	2181.31	342.53	454.99	2978.83	119.42
Composting (IPCC, 2006)	NA	2494.36	1783.96	NA	NA
Composting (EPA, 2024)	NA	NA	NA	2993.23	120.00
Anaerobic (Komakech et al., 2023)	1526.80	1055.20	454.99	3036.98	121.75
Anaerobic (IPCC, 2006)	NA	498.87	NA	NA	NA
Anaerobic (EPA, 2024)	NA	NA	NA	3741.53	150.00
Landfilling (IPCC, 2006)	NA	8190.84	NA	NA	NA
Landfilling (EPA, 2024)	NA	NA	NA	7732.50	310.00

NA: not available

4. CONCLUSION

This study demonstrates that Black Soldier Fly (BSF) larval bioconversion offers an effective and environmentally friendly approach for managing fruit and vegetable waste. Carbon conversion into BSF larval biomass ranged from 7.92% to 17.59%, while carbon conversion into residue ranged from 22.53% to 63.75%. Lower larval densities favored higher carbon conversion into larval biomass, though this was accompanied by reduced carbon retention in residue. Nitrogen conversion into larval biomass ranged from 4.96% to 21.69%, and into residue from 18.12% to 80.78%, with substrate composition and larval density showing no significant effect on nitrogen partitioning. Among the compared waste treatment methods, BSF bioconversion resulted in the lowest greenhouse gas emissions (102.27 g CO_2 eq/kg waste), highlighting its potential as a sustainable alternative to composting, anaerobic digestion, and landfilling. Furthermore, this study found that vegetable-based substrates supported better bioconversion performance than fruit-based mixtures, likely due to their lower moisture and sugar content that provided a more stable substrate condition and reduced microbial competition during larval feeding. These results suggest that the nutrient balance and physical characteristics of the substrate, together with optimal larval density, play important roles in determining the efficiency of BSF bioconversion of organic waste.

ACKNOWLEDGEMENT

This research was funded by the Indonesian Endowment Fund for Education (LPDP) through the Ministry of Education, Culture, Research, and Technology of Indonesia, and administered under the Indonesia–NTU Singapore Institute of Research for Sustainability and Innovation (INSPIRASI) program (Grant No. 6636/E3/KL.02.02/2023).

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