frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 05 January 2024
DOI 10.3389/fsufs.2023.1297858

OPEN ACCESS

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RECEIVED 20 September 2023
ACCEPTED 15 December 2023
PUBLISHED 05 January 2024

CITATION
Jasso B, Quinchia L, Waliczek TM and Drewery ML (2024) Black soldier fly larvae (*Hermetia illucens*) frass and sheddings as a compost ingredient.
Front. Sustain. Food Syst. 7:1297858.
doi: 10.3389/fsufs.2023.1297858

Black soldier fly larvae (*Hermetia illucens*) frass and sheddings as a compost ingredient

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One of the byproducts from rearing Black soldier fly larvae (BSFL) is its excrement, referred to as frass, and sheddings. As the commercial insect rearing industry is emerging in the U.S., there is not yet an established market for frass although the yield often exceeds that of BSFL by two- to three-fold. It has been suggested that frass could be converted into compost; however, there is a lack of literature investigating the effect of frass and larval sheddings inclusion on final compost quality. Accordingly, the objective of this study was to determine if BSFL frass and sheddings are a viable compost ingredient with the overarching purpose of identifying a potential market for an otherwise waste product of the insect-rearing industry. To address this objective, four experimental compost piles (6.12 m^3 each) with increasing levels of BSFL frass and sheddings (18.75, 22.87, 27.13, 31.25%) were developed. Across piles, wood chips (37.50%) and unscreened compost (18.75%) were consistent and frass and sheddings displaced food waste. Piles were mixed and tested for moisture and temperature weekly. Once internal temperatures decreased to 38°C, piles cured until internal temperatures were consistently <32°C. After curing, samples were collected from each pile and analyzed for pH, macro- and micro-nutrients, particle size, stability, and maturity. The entire composting process, including 2 months of curing, required 5 months. For each pile, pH, nitrogen, carbon, carbon:nitrogen, and potassium were within optimal ranges. Further, stability, measured as mg CO_2-C/g solids/day, and maturity, measured as seed emergence and seedling vigor, were also within optimal ranges. However, moisture/solids; organic matter; phosphorus; and stability, measured as mg CO_2-C/g organic matter/day, were out-of-specification for each pile given compost quality tests. Our findings indicate BSFL frass and sheddings may be a viable compost ingredient, but further research is recommended to establish optimal inclusion levels to maximize finished compost quality.

KEYWORDS

sustainability, insect protein, digestate, horticulture, circular economy, waste management

1 Introduction

Commercial insect production involves breeding and rearing insects for commercial, cosmetic, and/or nutritional applications. In the past two decades, infrastructure and knowledge required to rear insects for nutritional applications (i.e., as human food or animal feed) has advanced and the industry is continuing to scale as new technologies are implemented (Huynh et al., 2021). The Food and Agricultural Organization (FAO) estimates global meat consumption to increase by 14% from 2021 to 2030 due to population growth and urbanization (FAO, 2022).

With this growth, there is an increasing need for food and feed production that can be satisfied through insects (van Huis, 2013). Further, because global food production accounts for more than 50% of greenhouse emissions (Schmidt and Merciai, 2014), approximately one-third of which are related to livestock production, there is also a critical need to produce food and feed in a more environmentally sustainable manner.

Insect production places less pressure on natural resource and labor inputs than traditional food or feed as it requires minimal water, maintenance, and space (van Huis and Oonincx, 2017). Specifically, Black soldier fly larvae (BSFL, *Hermetia illucens*) has been evaluated as a protein source for livestock (Moorby and Fraser, 2021; Drewery et al., 2022; Fukuda et al., 2022). BSFL differs from conventional protein feeds in that its production has a lower environmental footprint. Production of conventional feeds, such as soy, is associated with deforestation, depletion of natural resources, contamination of resources (e.g., water contamination from pesticides), and greenhouse gas emissions (Poveda, 2021). BSFL can also be reared on surplus or uneaten food and animal waste, contributing to waste reduction by 50–60% (Shumo et al., 2019; Koon Ngee Tan et al., 2021; Singh et al., 2021).

Commercial insect rearing has potential to create a circular economy by rearing insects on food waste, producing a protein-rich larval biomass to be integrated into the food or feed chains and byproducts to be placed in other industries (Fowles and Nansen, 2020). One of the byproducts from rearing BSFL is its excrement, referred to as frass, and larval sheddings. As the commercial insect rearing industry is still emerging in the U.S., there is not yet an established market for frass although the yield could exceed that of BSFL by two- to three-fold (Salomone et al., 2017; Ravi et al., 2020). Identifying a market for frass could capture economic value for insect producers while also diverting organic waste from the landfill.

Previous researchers suggest that frass could be converted into compost (Song et al., 2021) and frass has been investigated as fish feed (Yildirim-Aksoy et al., 2020); however, most research has focused on the potential of frass as a fertilizer. If frass were to be used as fertilizer or compost, it could recycle nitrogen and phosphorus from the existing food chain and reduce demand for synthetic (i.e., chemical) fertilizers (Schmitt and de Vries, 2020). Recent research outlines models for commercial BSFL rearing and describes dried larval output of 150 tons per week (Suckling et al., 2021) which would conceivably be greater for frass. The potential for frass to capture economic value as compost or as a crop and soil health promoter has been posited, but not analyzed in detail given the immature frass market (Suckling et al., 2021).

Frass may be superior to synthetic fertilizers because it contains both macronutrients and micronutrients, whereas synthetic fertilizers only contain macronutrients (Houben et al., 2020). Further, frass is easily incorporated into plant roots and can return carbon, nitrogen, and ammonium to the soil (Poveda, 2021). Frass also decomposes faster than synthetic fertilizers, improving soil quality sooner (Houben et al., 2020). As a result, when applied as a fertilizer, frass can improve plant tolerance to environmental conditions, such as flooding and disease (Poveda, 2021). However, it has demonstrated that BSFL frass used as fertilizer can be detrimental to plant growth (Alattar et al., 2016).

Frass and larval sheddings contain chitin, a polymer present in the exoskeleton of insects and cell wall of fungi. Plants have enzymes that can digest chitin; however, activation of these enzymes also activates the plant's defense mechanisms (Wan and Stacey, 2008). Chitin can be almost completely mineralized by soil microorganisms in aerobic (oxic) conditions over a 20-day period (Wieczorek et al., 2019). Therefore, soil amendments containing chitin that have not been degraded through composting or similar processes may be detrimental to plant health and vitality. Compost studies conducted with waste wool or human hair and animal fur, keratin-containing organic materials, demonstrated that composting aided in progressing the degradation cycle to a point where nutrients were released (Hustvedt et al., 2016; Waliczek et al., 2023). However, hair wastes used directly in potting soil tied up nutrients (Zheljazkov, 2005). Chitin and keratin-rich soil amendments were found to react similarly in soils as conventional soil amendments while also aiding in disease-suppression in plants and increasing beneficial microbiology within soils (Andreo-Jimenez et al., 2021).

There have been limited investigations into frass and sheddings as a compost ingredient, although it has been described as having characteristics of immature compost (Xiao et al., 2020). Composting repurposes waste into valuable soil amendments which can then be applied to improve soil quality and plant growth/health. These improvements are critical in areas where agricultural advances are stunted by soil acidity, excessive aluminum, and calcium deficiencies, creating a market for compost industries that can be expanded with the use of traditionally discarded byproducts. Historically, composting has mainly involved the use of manure or discarded vegetation. However, in recent years, there has been more research on the efficacy of other organic materials as compost ingredients (Walsh and Waliczek, 2020; Waliczek et al., 2023) with the overarching goal of upcycling these materials from waste streams to valuable soil amendments.

The objective of this study was to determine if BSFL frass and sheddings are a viable compost ingredient with the overarching purpose of identifying a potential market for an otherwise waste product of the insect-rearing industry (i.e., frass) such that it is not a waste product, can be of economic value to the insect rearing industry, and can be of practical value to the horticultural and agricultural industries. To address this objective, BSFL frass and larval sheddings were included in four compost piles at increasing amounts and the effect on the composting process and final compost quality were evaluated.

2 Materials and methods

2.1 Material collection

BSFL frass and sheddings were sourced commercially. BSFL was fed pre-consumer food waste and frass and sheddings were pasteurized via heat treatment prior to incorporation in compost piles. Frass contained 92% dry matter (DM), 86% organic matter, 4% nitrogen, 54% neutral detergent fiber, and 19% acid detergent fiber. Wood chips were donated from a local tree care company from native and introduced regional species. Unscreened compost was collected at the Texas State University (San Marcos, TX) composting site. Pre- and post-consumer food waste was sourced from on-campus cafeterias at Texas State University (San Marcos, TX). Wood chips, unscreened compost, and food waste are often available and commonly utilized in small- and large-scale composting (Rynk and Schwarz, 2022). Despite wide-scale utilization and acceptance, the nitrogen, carbon, and moisture content, as well as structure and degradability, of wood chips and food waste vary by day and season (Rynk and Schwarz, 2022).

2.2 Development of compost piles

Four experimental compost piles with increasing levels of BSFL frass and sheddings were developed (Table 1). Across experimental piles, the amount of wood chips and unscreened compost were consistent (37.50 and 18.75%, respectively) while BSFL frass and sheddings displaced food waste as a nitrogen source. Inclusion levels of frass and sheddings was chosen based on previous research which also investigated the suitability of novel compost ingredients (Hustvedt et al., 2016; Waliczek et al., 2023). A true control pile of compost was not necessary because, in compost quality tests, samples are compared to overall compost quality standards for the industry (United States Composting Council Seal of Testing Assurance, 2010; Sembera et al., 2018, 2019; Walsh and Waliczek, 2020; Waliczek et al., 2023).

Unscreened compost was used to initiate composting in accordance with industry practices; by introducing mature compost and its microbes, decomposition of the new compost pile is facilitated (Oshins and Michel, 2022). To ensure appropriate microbial decomposition of organic material, compost piles individually totaled 6.12 m^3.

2.3 Compost development and maintenance

After developing the compost piles, each was mixed and tested at least weekly. When mixing the piles, water was added to maintain the ideal moisture conditions (40–60%) needed for the microbes to thrive and decompose waste products. Moisture and internal temperature were tested using a moisture meter and compost thermometer. These measurements were conducted from the time when the piles were initially developed through their activation states when internal temperatures plateaued and remained steady (approximately 54°C; Figure 1). Once internal temperatures decreased from 49 to 38°C, the piles reached the curing phase. During curing, piles were not mixed or watered, allowing them to reach their maximum microbial functionality and become stable (Pace et al., 1995).

Curing was complete once piles were consistently at a lower temperature range (<32°C) for 1 week. The entire curing process was approximately 2 months for an entire composting duration of approximately 5 months. After curing, samples of each pile were collected and tested for pH, macronutrients, micronutrients, particle size, stability, and maturity (United States Composting Council Seal of Testing Assurance, 2010). Samples were also collected from each pile 3 months after the initial collection (total curing time of 5 months and composting duration of 8 months) to evaluate if a longer composting time translated to higher quality compost given the findings of Al-Bataina et al. (2016) that curing length impacts physical and chemical characteristics of compost. To ensure samples were representative of the compost pile, equal amounts were taken from the center, top, and bottom of each pile and composited within pile. The quality measures for each pile were then compared to the established optimal or normal ranges of mature compost (United States Composting Council Seal of Testing Assurance, 2010; Ozores-Hampton, 2017) as a positive control.

3 Results

3.1 Composting process

Temperature profiles of each pile are displayed in Figure 1. Initial temperatures (day 1) of the piles ranged from 34 to 54°C; this variation likely resulted from the environmental temperature on the day of pile development as each pile was not developed on the same calendar day. Within the first 14 days, pile temperatures rose and plateaued at an average of 60°C. Pile temperature noticeably and consistently dropped across all piles around day 70 with incremental declines through day 105 where temperature plateaued from 31 to 37°C until another decrease around day 145. At this point, piles cured until approximately day 160 when the target temperature (approximately 38°C) was maintained over the course of 1 week.

TABLE 1 Composition of experimental compost piles containing Black soldier fly larvae frass and sheddings.

	Wood chips	Unscreened compost	Frass and sheddings	Food waste	Total
Pile A					
Inclusion	37.50%	18.75%	18.75%	25.00%	100%
Amount	2.29 m^3	1.15 m^3	1.15 m^3	1.53 m^3	6.12 m^3
Pile B					
Inclusion	37.50%	18.75%	22.87%	20.88%	100%
Amount	2.29 m^3	1.15 m^3	1.40 m^3	1.28 m^3	6.12 m^3
Pile C					
Inclusion	37.50%	18.75%	27.13%	16.63%	100%
Amount	2.29 m^3	1.15 m^3	1.66 m^3	1.02 m^3	6.12 m^3
Pile D					
Inclusion	37.50%	18.75%	31.25%	12.50%	100%
Amount	2.29 m^3	1.15 m^3	1.91 m^3	0.77 m^3	6.12 m^3

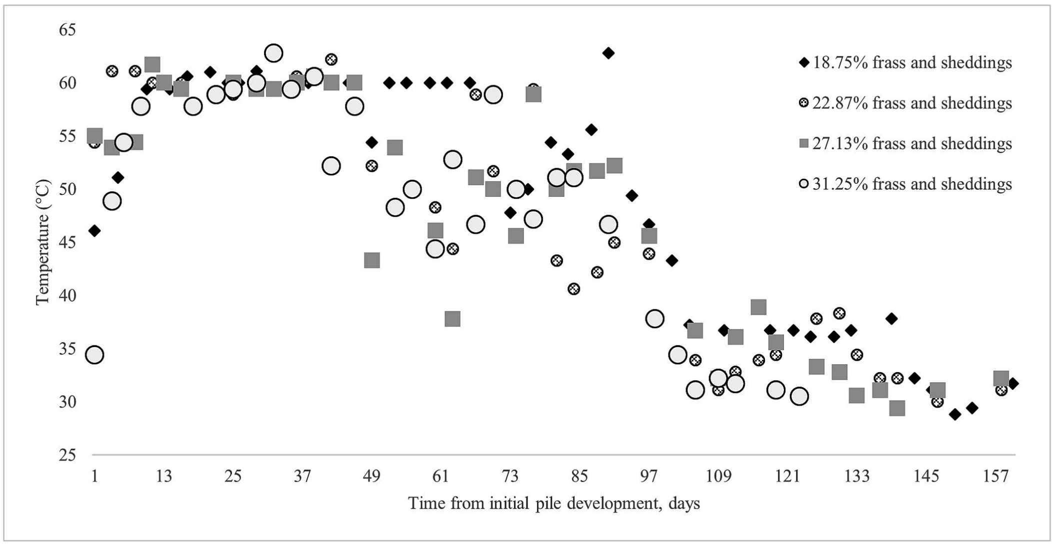

FIGURE 1
Temperature profile of compost piles containing Black soldier fly larvae frass and sheddings.

The pile containing the most BSFL frass and sheddings (31.25%) required the shortest amount of time to compost completion, hitting the target curing parameters on day 123 versus day 158 for the piles containing 22.87 and 31.25% frass and sheddings and on day 160 for the pile containing the amount of frass and sheddings (18.75%). Anecdotally, we also observed the physical size of the pile containing 31.25% frass and sheddings was noticeably larger than the pile containing 18.75% after composting; however, all piles decreased by approximately 50% of their starting volume which was as expected (Ozores-Hampton et al., 2021).

3.2 Compost quality test

Quality measures of each pile are outlined in Table 2 for samples taken after 5 months of composting (2 months of curing) and in Table 3 for samples taken after 8 months of composting (5 months of curing). For all samples, quality measures are compared to normal and optimal ranges defined by United States Composting Council Seal of Testing Assurance (2010) and Ozores-Hampton (2017). Indices within optimal ranges indicate the compost meets the desired criteria for quality and effectiveness.

For samples taken during the first collection (i.e., 5 months of composting), the pH for all piles was within the optimal range of 5.0–8.0 excluding that of the pile with the lowest frass inclusion which had a pH of 8.1. Solids were out-of-specification for all piles, ranging from 80.0 to 84.5%. Consequently, moisture content was lower than optimal, ranging from 15.5 to 20.0% across piles. Organic matter was also below the minimum for all piles; the optimal range is 40–60% and the piles ranged from 30.4 to 34.2% on a DM basis. Total nitrogen, carbon, carbon:nitrogen ratio, and potassium for all piles were within optimal ranges. The optimal range of phosphorus is 0.2–0.3%; samples from all piles greatly exceeded this with the lowest value observed for the pile containing 18.75% frass and sheddings (1.20% DM) and the highest value observed for the pile containing 31.25% frass and sheddings (1.40% DM). There is not an established optimal value for NPK ratio of compost; however, NPK of the pile containing the greatest frass inclusion was clearly impacted by the relatively high P and low K levels (2.5:1.8:1). Stability, measured as mg CO_2-C/g organic matter/day, exceeded the optimal value (<2) for each pile with the pile containing 27.13% BSFL frass and sheddings having the value that was the most out-of-specification (8.3). However, when stability was measured as mg CO_2-C/g solids/day, all piles were within specification. Further, maturity, measured as seed emergence and as seedling vigor, was within specification (>90 for both) and every pile was classified as "very mature."

For samples taken during the second collection (i.e., 5 months of curing), the pH for all piles was within the optimal range of 5.0–8.0. Solids were out-of-specification for all piles, ranging from 84.9 to 91.3% and moisture was lower than optimal, ranging from 8.7 to 15.1%. Organic matter was also below the minimum for all piles, ranging from 28.5 to 35.3% DM. Total nitrogen, carbon, carbon:nitrogen ratio, and potassium for all piles were within optimal ranges. As with the samples taken after 2 months of curing, the phosphorus content of samples taken after 5 months of curing was much higher than the optimal value, ranging from 1.22 to 1.75% DM. NPK ratios were closely grouped across piles, with an overall average of 2.2:1.8:1. The compost piles were not stable in terms of mg CO_2-C/g organic matter/day. When stability was measured as mg CO_2-C/g solids/day, however, the pile containing 27.13% frass and sheddings was not stable (2.7) although the others were within specification (<2). Piles at the lower inclusion levels of BSFL frass and sheddings were mature, when measured as seed emergence, although the piles containing 27.13 and 31.25% of frass and sheddings were not. However, when maturity was measured as seedling vigor, all piles were classified as "very mature."

4 Discussion

The objective of this study was to evaluate BSFL frass and sheddings as a compost ingredient with the overarching goal of

TABLE 2 Quality of piles composted for 5 months (2 months of curing) containing Black soldier fly larvae frass and sheddings.

Variable (units)[a]	18.75% frass and sheddings	22.87% frass and sheddings	27.13% frass and sheddings	31.25% frass and sheddings	Optimal range[b]
pH	8.10	8.00	8.00	7.70	5.0–8.0
Solids (%)	84.30	80.00	84.50	81.40	40–70
Moisture (%)	15.70	20.00	15.50	18.60	30–60
Organic matter (%)	30.40	32.30	32.00	34.20	40–60
Total nitrogen (%)	1.70	1.70	1.70	1.90	0.5–6.0
Carbon (%)	19.10	17.90	19.40	20.10	<54
Carbon:nitrogen ratio	11.10	10.80	11.20	10.60	10–25
Phosphorus (%)	1.20	1.22	1.28	1.40	0.2–0.3
Potassium (%)	0.93	0.96	0.98	0.77	0.10–3.5
Calcium (%)	15.79	15.00	14.71	14.98	–
Magnesium (%)	0.48	0.52	0.50	0.50	–
NPK ratio	1.9:1.3:1	1.8:1.3:1	1.7:1.3:1	2.5:1.8:1	–
Particle size (% <9.5 mm)	94.18	89.76	93.88	91.09	–
Stability					
mg $CO_{2\text{-C/g solids/day}}$	1.00	1.00	2.70	1.40	<2
mg $CO_{2\text{-C/g organic matter/day}}$	3.30	3.20	8.30	4.10	<2
Maturity					
Seed emergence, % control	93.33	90.00	93.33	100.00	>90
Seedling vigor, % control	100.00	100.00	100.00	100.00	>95

[a]pH, solids, moisture, and particle size are reported on an as-is basis while the remaining variables are reported on a dry matter basis; [b]Optimal ranges established by United States Composting Council Seal of Testing Assurance (2010) and Ozores-Hampton (2017), except for NPK ratio.

TABLE 3 Quality of piles composted for 8 months (5 months of curing) containing Black soldier fly larvae frass and sheddings.

Variable (units)[a]	18.75% frass and sheddings	22.87% frass and sheddings	27.13% frass and sheddings	31.25% frass and sheddings	Optimal range[b]
pH	7.80	7.70	7.70	7.90	5.0–8.0
Solids (%)	91.30	84.90	90.60	90.80	40–70
Moisture (%)	8.70	15.10	9.40	9.20	30–60
Organic matter (%)	28.50	34.30	35.30	32.30	40–60
Total nitrogen (%)	1.70	1.80	1.90	1.70	0.5–6.0
Carbon (%)	18.40	19.90	19.90	18.60	<54
Carbon:nitrogen ratio	10.80	11.10	10.60	10.90	10–25
Phosphorus (%)	1.22	1.30	1.37	1.75	0.2–0.3
Potassium (%)	0.78	0.82	0.82	0.84	0.10–3.5
Calcium (%)	15.85	14.72	15.43	16.23	–
Magnesium (%)	0.51	0.49	0.51	0.51	–
NPK ratio	2.2:1.6:1	2.2:1.6:1	2.3:1.7:1	2.0:2.1:1	–
Particle size (% <9.5 mm)	100.00	100.00	100.00	100.00	–
Stability					
mg $CO_{2\text{-C/g solids/day}}$	1.30	1.70	2.70	1.40	<2
mg $CO_{2\text{-C/g organic matter/day}}$	4.60	5.30	8.50	4.60	<2
Maturity					
Seed emergence, % control	100.00	100.00	33.33	66.67	>90
Seedling vigor, % control	100.00	100.00	100.00	100.00	>95

[a]pH, solids, moisture, and particle size are reported on an as-is basis while the remaining variables are reported on a dry matter basis. [b]Optimal ranges established by United States Composting Council Seal of Testing Assurance (2010) and Ozores-Hampton (2017), except for NPK ratio.

determining a potential market for frass such that it is not a waste product, can be of economic value to the insect rearing industry, and can be of practical value to the horticultural and agricultural industries. We developed various compost piles and replaced food waste with increasing proportions of BSFL frass. Although food waste is a valuable compost ingredient, there may be challenges with using it in compost and not all countries and/or regions have infrastructure in place for large-scale food waste collections and/or composting (Cerda et al., 2018). The insect rearing industry is not dependent on seasonality and, when BSFL frass is dried, it is shelf stable and easy to transport or store without further transformation or stabilization (Salomone et al., 2017). Therefore, frass may represent a year-round nitrogen source that is available when food waste or another nitrogen source cannot be collected and/or during periods of deficits.

Our findings indicate there are challenges with using frass and larval sheddings as a compost ingredient at inclusion levels of 18.75–31.25% as some parameters were out-of-specification for samples collected after 5 and 8 months of composting. Specifically, compost piles containing BSFL frass and sheddings had levels of solids, moisture, organic matter, and phosphorus that were not optimal. Further, some piles were also unstable and/or immature, depending on the time of sampling and testing procedure. Despite this, positive outcomes were observed for other stability and maturity parameters. Ultimately, this preliminary analysis indicates further investigation is needed to fully determine if BSFL frass and sheddings may be viable compost ingredients.

The difference in physical size of the compost piles we observed could be due to the particle size and moisture content of frass versus that of food waste as these ingredients were substituted for each another. It is generally easier for piles that are physically larger and/or denser to reach and maintain internal temperatures (Rynk et al., 1992; Oshins and Michel, 2022), facilitating and expediting the composting process, which could explain why the pile containing the highest amount of frass and larval sheddings reached compost completion the quickest. Additionally, small materials with greater surface area decompose more rapidly (Rynk et al., 1992; Oshins and Michel, 2022).

Physiochemical characteristics of BSFL frass varies and depends on the environment the larvae are reared in, especially what substrate they are reared on (Basri et al., 2022). The pH of frass from BSFL reared on food waste ranges from 5.6 to 8.0 (Ritika and Rajendra, 2015; Gao et al., 2019; Klammsteiner et al., 2020) with most frass in the pH 7.0–8.0 range (Basri et al., 2022). The average pH of samples from our compost piles containing BSFL frass and sheddings was 8.0 after 5 months of composting and 7.8 after 8 months of composting, which is acceptable for plant growth.

The moisture content of compost that includes BSFL frass may introduce challenges for practical use. For the first sampling, after 5 months of composting, average moisture was 17.5% and, for the second sampling, after 8 months of composting, average moisture was 10.6%. Practically, this could create excessive dust when transporting and spreading compost (Stehouwer et al., 2022) and could also cause hydration or rewetting challenges. It is unclear if the low moisture content we observed was a consequence of the presence of frass and larval sheddings; reflects the time between sampling, shipping, and laboratory analysis, providing opportunity for samples to dehydrate; and/or was due to remnants of the wood chip feedstock remaining in the compost samples since they were not screened during sampling. Fresh frass excreted from BSFL reared on spent brewery grains can contain 30% moisture (Beesigamukama et al., 2020); however, the frass we used was commercially obtained and dried as part of a pasteurization process. In a different analysis by our laboratory, the same frass as used in the current trial was 93.5% DM (Rea, 2022) and, therefore, could have reasonably contributed to the observed low moisture of finished piles.

The nutrient content (i.e., NPK) of fertilizer and soil amendments is of critical importance. Frass nitrogen content is generally close to 2% (Beesigamukama et al., 2020; Kawasaki et al., 2020; Klammsteiner et al., 2020); the nitrogen content of our compost samples was within specification and ranged from 1.7 to 1.9%. Noticeably, however, the phosphorus content of our samples was much greater than the specified "normal" range (0.2–0.3%). There were parallel increases in phosphorus content and inclusion of BSFL frass and sheddings, indicating frass was the ingredient responsible for high phosphorus content in our compost samples. BSFL frass can contain phosphorus from 1.0 to 2.5%, depending on rearing substrate (Gao et al., 2019; Beesigamukama et al., 2020; Song et al., 2021); therefore, high phosphorus is likely an intrinsic characteristic of frass. Thus, compost that contains frass will inherently have phosphorus levels that are outside of the established normal range, but this is not necessarily a detriment for horticultural or agricultural applications. It is common for composts with high inclusion of bonemeal, shellfish, hair, manures, feathers, or mushroom bedding to have high phosphorus content (Nayaka and Vidyasagar, 2013; Wei et al., 2015) and these composts can be beneficial for triggering flowering and fruiting on crops or for increasing root growth during transplanting (Bhadouria and Giri, 2022). Further, given that commercial organic fertilizers commonly have phosphorus of approximately 2.3% and chemical fertilizers of approximately 16%, the practical consequences of utilizing a frass-containing compost on plant and soil health as a result of elevated phosphorus are likely minimal.

Carbon:nitrogen gives an indication of compost stability and nitrogen availability; the established range is 10–25. Although on the lower end, samples from every compost pile at both timepoints were within this established range. Compost with a carbon:nitrogen of <20 is desirable as it indicates organic nitrogen has mineralized to its inorganic form and is available for plant absorption; if carbon:nitrogen >30, nitrogen is more likely to be immobilized and unavailable for plant uptake (Sarpong et al., 2019). In previous research where BSFL frass was composted with forced aeration or naturally in a rearing chamber with prepupae for 5 weeks, carbon:nitrogen was 9.6 and 7.0, respectively (Song et al., 2021). Therefore, we achieved ideal carbon:nitrogen with 18.75–31.25% of frass inclusion after composting for approximately 5 months, although the composting protocols of Sarpong et al. (2019) did not yield the same outcome. Despite our compost piles achieving normal carbon:nitrogen, there were mixed results for stability and maturity, depending on the test (i.e., stability measured as mg CO_2-C/g solids/day or mg CO_2-C/g organic matter/day; maturity measured as seed emergence or seedling vigor) and time of sampling (i.e., after 5 or 8 months of composting).

Previous research indicates that Pak choi plants cultivated in a mixture of composted BSFL frass and biochar had more biomass accumulation and leaf numbers than plants cultivated in fresh frass mixtures or with biochar alone (Song et al., 2021). These observations indicate a benefit for composting frass, likely reflecting the effect of composting on phytotoxin levels inherent in fresh frass (Song et al., 2021) and, potentially, on chitin. Other researchers also recommend post-treating of frass to ensure its maturity and stability (Lopes et al., 2022). Our study is limited in that we did not evaluate the impact of our finished compost on plant growth or health. However, as samples collected from each compost pile after 5 months of composting had optimal maturity when measured as either seed emergence or seedling vigor, we anticipate phytotoxins and/or chitin in our compost piles were adequately reduced or hydrolyzed to support plant growth.

We did not conduct an analysis of heavy metal accumulation in BSFL frass and the resulting impacts on compost quality in the current study. This was justified based on previous research. As BSFL naturally feed on organic waste, they accumulate and retain heavy metals in their biomass and their frass contains low amounts of metals (Attiogbe et al., 2019; Sarpong et al., 2019). Further, BSFL reared in the U.S. must be fed on feed grade or better materials (AAFCO, 2021), indicating there would not be significant exposure to heavy metals through the dietary substrate and that heavy metal content of frass would not be a concern when commercially obtained in the U.S.

Previous researchers have suggested that BSFL frass is an immature compost and requires post-treatment (Kawasaki et al., 2020; Song et al., 2021). In this study, we evaluated the effect of including BSFL frass and sheddings from 18.75 to 31.25% on finished compost quality. While certain macronutrients, micronutrients, maturity, and stability indicators were within established normal ranges, others were out-of-specification. In studies of waste wool and hair, a high moisture and nitrogen fish waste feedstock needed to be incorporated at increased rates to aid in decomposition (Hustvedt et al., 2016; Waliczek et al., 2023). Since chitin, which is found in BSFL frass and sheddings, is fibrous and similar to keratin, which is found in wool and hair, adding feedstocks with high moisture and nitrogen may be helpful in future studies that compost BSFL frass and sheddings. Additionally, it is recommended that samples be screened to 0.6–1.3 cm particles as is the industry standard for particular types of applications to ensure a more accurate representation of the solid to moisture levels of the finished compost (Ozores-Hampton et al., 2021). We did not screen our samples prior to quality analysis and this limits our ability to interpret solids and moisture level.

Ultimately, further research is needed to replicate our findings, evaluate a wider range of BSFL frass and sheddings inclusion on finished compost quality, and evaluate the effect of applying compost containing BSFL frass and sheddings on plant growth and health. We also recommend investigations into other potential applications of frass and larval sheddings in the horticultural and agricultural industries to identify a feasible market for this byproduct and add economic and environmental value to the emerging insect rearing industry.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

BJ: Data curation, Investigation, Writing – original draft. LQ: Data curation, Investigation, Writing – original draft. TW: Conceptualization, Formal analysis, Resources, Supervision, Writing – review & editing. MD: Conceptualization, Formal analysis, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. The authors acknowledged funding from United States Department of Agriculture (USDA) Hispanic Serving Institutions program (grant 2020–01979).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

AAFCO. (2021). *Ingredient definitions committee report midyear meeting via webinar*, version 4. Available at: https://www.aafco.org/Portals/0/SiteContent/Meetings/Annual/2021/Committee-Reports/Ingredient_Definitions_Minutes_2021_Midyear.pdf.

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

Al-Bataina, B. B., Young, T. M., and Ranieri, E. (2016). Effects of compost age on the release of nutrients. *Int. Soil Water Conserv. Res.* 4, 230–236. doi: 10.1016/j.iswcr.2016.07.003

Andreo-Jimenez, B., Schilder, M. T., Nijhuis, E. H., te Beest, D. E., Bloem, J., Visser, J. H. M., et al. (2021). Chitin- and keratin-rich soil amendments suppress *Rhizoctonia solani* disease via changes to the soil microbial community. *Microb. Ecol.* 87, e00318–e00321. doi: 10.1128/AEM.00318-21

Attiogbe, F. K., Ayim, N. Y. K., and Martey, J. (2019). Effectiveness of black soldier fly larvae in composting mercury contaminated organic waste. *Sci. Afr.* 6:e00205. doi: 10.1016/j.sciaf.2019.e00205

Basri, N. E. A., Azman, N. A., Ahmad, I. K., Suja, F., Jalil, N. A. A., and Amrul, N. F. (2022). Potential applications of frass derived from black soldier fly larvae treatment of food waste: a review. *Foods* 11:2664. doi: 10.3390/foods11172664

Beesigamukama, D., Mochoge, B., Korir, N. K., Fiaboe, K. K. M., Nakimbugwe, D., Khamis, F. M., et al. (2020). Exploring black soldier fly frass as novel fertilizer for improved growth, yield, and nitrogen use efficiency of maize under field conditions. *Front. Plant Sci.* 11:574592. doi: 10.3389/fpls.2020.574592

Bhadouria, J., and Giri, J. (2022). Purple acid phosphatases: roles in phosphate utilization and new emerging functions. *Plant Cell Rep.* 41, 33–51. doi: 10.1007/s00299-021-02773-7

Cerda, A., Artola, A., Font, X., Barrena, R., Gea, T., and Sanchez, A. (2018). Composting of food wastes: status and challenges. *Bioresour. Technol.* 248, 57–67. doi: 10.1016/j.biortech.2017.06.133

Drewery, M. L., Liu, X., and Wickersham, T. A. (2022). Black soldier fly larvae (BSFL) as a feed for beef cattle: a hedonic pricing model. *J. Insects Food Feed* 8, 743–751. doi: 10.3920/JIFF2021.0166

FAO (2022). *OECD-FAO agricultural outlook 2022–2031*. OECD Publishing: Paris.

Fowles, T. M., and Nansen, C. (2020). "Insect-based bioconversion: value from food waste" in *Food waste management*. eds. E. Närvänen, N. Mesiranta, M. Mattila and A. Heikkinen (Cham: Palgrave Macmillan)

Fukuda, E. P., Cox, J. R., Wickersham, T. A., and Drewery, M. L. (2022). Evaluation of black soldier Fly larvae (*Hermetia illucens*) as a protein supplement for beef steers consuming low-quality forage. *Transl. Anim. Sci.* 6, 1–6. doi: 10.1093/tas/txac018

Gao, Z., Wang, W., Lu, X., Zhu, F., Liu, W., Wang, X., et al. (2019). Bioconversion performance and life table of black soldier fly (*Hermetia illucens*) on fermented maize straw. *J. Clean. Prod.* 230, 974–980. doi: 10.1016/j.jclepro.2019.05.074

Houben, D., Daoulas, G., Faucon, M.-P., and Dulaurent, A.-M. (2020). Potential use of mealworm frass as a fertilizer: impact on crop growth and soil properties. *Sci. Rep.* 10, 4659–4652. doi: 10.1038/s41598-020-61765-x

Hustvedt, G., Meier, E., and Waliczek, T. M. (2016). The feasibility of large-scale composting of waste wool in *Green fashion, environmental footprints and eco-design of products and processes*, vol. *11*, Eds. Muthu, S. S. and M. A. Gardetti Singapore: Springer Science + Business Media, 95–107.

Huynh, M. P., Shelby, K. S., and Coudron, T. A. (2021). Recent advances in insect rearing methodology to promote research and mass production. *Insects* 12:961. doi: 10.3390/insects12110961

Kawasaki, K., Kawasaki, T., Hirayasu, H., Matsumoto, Y., and Fujitani, Y. (2020). Evaluation of fertilizer value of residues obtained after processing household organic waste with black soldier fly larvae (*Hermetia illucens*). *Sustainability* 12:4920. doi: 10.3390/su12124920

Klammsteiner, T., Turan, V., Juárez, M. F.-D., Oberegger, S., and Insam, H. (2020). Suitability of black soldier Fly frass as soil amendment and implication for organic waste hygienization. *Agronomy* 10:1578. doi: 10.3390/agronomy10101578

Koon Ngee Tan, J., Tian En Lee, J., Zhongyu, C., Shuang, S., Srishti, A., Yen Wah, T., et al. (2021). Applications of food waste-derived black soldier fly larval frass as incorporated compost, side-dress fertilizer and frass-tea drench for soilless cultivation of leafy vegetables in biochar-based growing media. *Waste Manag.* 130, 155–166. doi: 10.1016/j.wasman.2021.05.025

Lopes, I. G., Yong, J. W., and Lalander, C. (2022). Frass derived from black soldier fly larvae treatment of biodegradable wastes. A critical review and future perspectives. *Waste Manag.* 142, 65–76. doi: 10.1016/j.wasman.2022.02.007

Moorby, J. M., and Fraser, M. D. (2021). Review: new feeds and new feeding systems in intensive and semi-intensive forage-fed ruminant livestock systems. *Int. J. Anim. Biosci.* 15:100297. doi: 10.1016/j.animal.2021.100297

Nayaka, S., and Vidyasagar, G. (2013). Development of eco-friendly bio-fertilizer using feather compost. *Ann. Plant Sci.* 2, 238–244.

Oshins, C., and Michel, F. (2022). "The composting process" in *The composting handbook*. ed. R. Rynk (Cambridge, Massachusetts, US: Academic Press), 51–101.

Ozores-Hampton, M. (2017). Guidelines for assessing compost quality for safe and effective utilization in vegetable production. *HortTechnology* 27, 162–165. doi: 10.21273/HORTTECH03349-16

Ozores-Hampton, M., Biala, J., Evanylo, G., Faucette, B., Cooperband, L., Roe, N., et al. (2021). "Compost use" in *The composting handbook*. ed. R. Rynk (Massachusetts, US: Academic Press), 777–846.

Pace, M. G., Miller, B. E., and Farrell-Poe, K. L. (1995). *The composting process* Utah State University Available at: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1047&context=extension_histall.

Poveda, J. (2021). Insect frass in the development of sustainable agriculture. A review. *Agron. Sust. Agric.* 41, 1–10. doi: 10.1007/s13593-020-00656-x

Ravi, H. K., Degrou, A., Costil, J., Trespeuch, C., Chemat, F., and Vian, M. A. (2020). Larvae mediated valorization of industrial, agriculture and food wastes: biorefinery concept through bioconversion, processes, procedures, and products. *Processes* 8:857. doi: 10.3390/pr8070857

Rea, J. C. (2022) *Evaluating multiple edible insects as feed for cattle: an in-vitro analysis.* [Bachelor's honor thesis], San Marcos, TX: Texas State University. Available at: https://digital.library.txstate.edu/handle/10877/16144.

Ritika, P., and Rajendra, S. S. P. (2015). Study on occurrence of black soldier fly larvae in composting of kitchen waste. *Int. J. Res. Biosci.* 4, 38–45.

Rynk, R., and Schwarz, M. (2022). "Compost feedstocks" in *The composting handbook*. ed. R. Rynk (Academic Press), 103–157. Available at: https://www.sciencedirect.com/science/article/abs/pii/B9780323856027000054

Rynk, R., van de Kamp, M., Wilson, G. B., Singley, M. E., Richard, T. L., Kolega, J. J., et al. (1992). "On-farm composting handbook" in *Natural resource, agriculture, and engineering service* (Ithaca, NY) Available at: https://campus.extension.org/pluginfile.php/48384/course/section/7167/NRAES%20FarmCompost%20manual%201992.pdf

Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S., and Savastano, D. (2017). Environmental impact of food waste bioconversion by insects: application of life cycle assessment to process using *Hermetia illucens*. *J. Clean. Prod.* 140, 890–905. doi: 10.1016/j.jclepro.2016.06.154

Sarpong, D., Oduro-Kwarteng, S., Gyasi, S. F., Buamah, R., Donkor, E., Awuah, E., et al. (2019). Biodegradation by composting of municipal organic solid waste into organic fertilizer using the black soldier fly (*Hermetia illucens*) (Diptera: Stratiomyidae) larvae. *Int. J. Recycl. Org. Waste Agric.* 8, 45–54. doi: 10.1007/s40093-019-0268-4

Schmidt, J. H., and Merciai, S. (2014). "Life cycle assessment of the global food consumption" in *In: 9th international conference LCA of food* (San Francisco, CA), 8–10. Available at: https://lca-net.com/files/LCAfood2014-LCAofGlobalFoodConsumption.pdf

Schmitt, E., and de Vries, W. (2020). Potential benefits of using *Hermetia illucens* frass as a soil amendment on food production and for environmental impact reduction. *Curr. Op. Green Sustain. Chem.* 25:100335. doi: 10.1016/j.cogsc.2020.03.005

Sembera, J., Meier, E., and Waliczek, T. M. (2018). Composting as an alternative management for sargassum drifts on coastlines. *HortTechnology* 28, 80–84. doi: 10.21273/HORTTECH03836-17

Sembera, J. A., Waliczek, T. M., and Meier, E. J. (2019). Composting as an alternative management for wild taro (*Colocasia esculenta*). *HortTechnology* 29, 205–209. doi: 10.21273/HORTTECH04194-18

Shumo, M., Osuga, I. M., Khamis, F. M., Tanga, C. M., Fiaboe, K. K. M., Subramanian, S., et al. (2019). The nutritive value of black soldier fly larvae reared on common organic waste streams in Kenya. *Sci. Rep.* 9:10110. doi: 10.1038/s41598-019-46603-z

Singh, A., Srikanth, B. H., and Kumari, K. (2021). Determining the black soldier fly larvae performance for plant-based food waste reduction and the effect on biomass yield. *Waste Manag.* 130, 147–154. doi: 10.1016/j.wasman.2021.05.028

Song, S., Ee, A. W., Tan, J. K., Cheong, J. C., Chiam, Z., Arora, S., et al. (2021). Upcycling food waste using black soldier fly larvae: effects of further composting on frass quality, fertilizing effect and its global warming potential. *J. Clean. Prod.* 288:125664. doi: 10.1016/j.jclepro.2020.125664

Stehouwer, R., Cooperband, L., Rynk, R., Biala, J., Bonhotal, J., Antler, S., et al. (2022). "Compost characteristics and quality" in *The composting handbook*. ed. R. Rynk (Academic Press), 737–775.

Suckling, J., Druckman, A., Small, R., Ceclja, F., and Bussemaker, M. (2021). Supply chain optimization and analysis of *Hermetia illucens* (black solder fly) bioconversion of surplus foodstuffs. *J. Clean. Prod.* 321:128711. doi: 10.1016/j.jclepro.2021.128711

United States Composting Council Seal of Testing Assurance. (2010). Available at: https://www.compostingcouncil.org/page/CertifiedCompostSTA.

van Huis, A. (2013). Potential of insects as food and feed in assuring food security. *Ann. Rev. Entomol.* 58, 563–583. doi: 10.1146/annurev-ento-120811-153704

van Huis, A., and Oonincx, D. G. A. B. (2017). The environmental sustainability of insects as food and feed. A review. *Agron. Sustain. Dev.* 37:43. doi: 10.1007/s13593-017-0452-8

Waliczek, T. M., Drewery, M., McMoran, A., Eriksen, M., and Hale, J. (2023). Assessing the quality of compost produced from human hair and pet fur waste. *Compost Sci. Utiliz.* 29, 57–64. doi: 10.1080/1065657X.2023.2167749

Walsh, K., and Waliczek, T. M. (2020). Examining the quality of a compost product derived from sargassum. *HortTechnology* 30, 331–336. doi: 10.21273/HORTTECH04523-19

Wan, J., Zhang, X-C., Stacey, G. (2008). Chitin signaling and plant disease resistance. *Plant Signal. Behav.* 3: 831–833. doi: 10.4161/psb.3.10.5916

Wei, Y., Zhao, Y., Xi, B., Wei, Z., Li, X., and Cao, Z. (2015). Changes in phosphorus fractions during organic wastes composting from different sources. *Biores. Tech.* 189, 349–356. doi: 10.1016/j.biortech.2015.04.031

Wieczorek, A. S., Schmidt, O., Chatzinotas, A., von Bergen, M., Gorissen, A., and Kolb, S. (2019). Ecological functions of agricultural soil bacteria and microeukaryotes in chitin degradation: a case study. *Front. Microbiol.* 10:1293. doi: 10.3389/fmicb.2019.01293

Xiao, Y., Geng, W., Yang, Y., Wang, X., and Xu, X. (2020). Study on the difference of transformation of livestock and poultry feces by black soldier fly. In: Proceedings of IOP Conference Series: Earth and Environmental Science, Xi'an, China.

Yildirim-Aksoy, M., Eljack, R., Schrimsher, C., and Beck, B. (2020). Use of dietary frass from black soldier fly larvae, *Hermetia illucens*, in hybrid tilapia (Nile × Mozambique, *Oreocromis niloticus* × *O. Mozambique*) diets improves growth and resistance to bacterial diseases. *Aquacul. Rep.* 17:100373. doi: 10.1016/j.aqrep.2020.100373

Zheljazkov, V. D. (2005). Assessment of wool waste and hair waste as soil amendment and nutrient source. *J. Environ. Qual.* 34, 2310–2317. doi: 10.2134/jeq2004.0332