Hapres | Journal of Sustainability Research
sustainability.hapres.com

Article

Increasing Rates of Black Soldier Fly (*Hermetia illucens*) Larval Frass Incorporation in African Marigold (*Tagetes erecta*) Production

Maria Y. Chavez [1,*], Jake Holley [2], Joshua K. Craver [3], Ciro Velasco-Cruz [4], Jennifer Bousselot [3]

[1] Department of Plant and Environmental Sciences, Agricultural Science Center at Farmington, New Mexico State University, 300 Road 4063, Farmington, NM 87401, USA

[2] Metropolitan Agricultural Research Center, Colorado State University Spur, Denver, CO 80216, USA; Jake.Holley@colostate.edu (JH)

[3] Department of Horticulture and Landscape Architecture, Colorado State University, Fort Collins, CO 80523, USA; Joshua.Craver@colostate.edu (JKC); Jennifer.Bousselot@colostate.edu (JB)

[4] Department of Agricultural Economics & Agricultural Business, New Mexico State University, Las Cruces, NM 88003, USA; cvelasco@nmsu.edu (CV-C)

* Correspondence: Maria Y. Chavez, Email: mychavez@nmsu.edu;
Tel.: +1-505-960-7757.

Received: 20 Dec 2025
Accepted: 15 Apr 2026
Published: 29 Apr 2026

ABSTRACT

Black soldier fly (*Hermetia illucens*) larvae (BSFL) are popular decomposers capable of reducing food waste and producing frass, a promising substrate additive and fertility product. Frass has gained interest in horticultural production as a more sustainable, partial replacement for fertilizers, and especially peat moss based potting mixes. This has been studied in vegetable and food crops, but has not been thoroughly explored in ornamental crops. Marigolds (*Tagetes erecta* var. 'Inca II') were grown in a peat-moss–based potting mix amended with BSFL frass at 10, 20, or 40% by volume, and were compared to marigolds grown in an unamended peat-based potting-mix control. The BSFL 40% treatment produced negative results for plant size and weight, and replicates in this treatment did not flower. The marigolds grown in the BSFL 10% were statistically comparable to marigolds grown in the control in all parameters. There were no significant differences in relative flavonoid and anthocyanin concentrations of the flowers based on treatment. Electrical conductivity (EC) was significantly higher in the high concentration of frass, BSFL 40%, likely due to the higher sodium concentrations in the frass. The water holding capacity (WHC) of these treatments was also evaluated and results indicate there were no significant differences in the WHC of the treatment percentages. Similar to vegetable studies, low concentrations of frass (10–20%) appear to be an effective media replacement. In order to incorporate larger quantities of frass into crop production, alternative approaches to frass use must be considered. Washing frass to reduce sodium concentrations or altering larval diet to reduce ammonium concentrations should be considered. This project warrants more research in pretreating frass in horticultural production prior to application.

KEYWORDS: ornamental; substrate; peat-based potting mix; frass; plant size at harvest; stomatal conductance; water holding capacity; electrical conductivity

ABBREVIATIONS

BSFL, black soldier fly larvae; CEA, controlled environment agriculture; DW, dry weight; SC, stomatal conductance; PSH, plant size at harvest; EC, electrical conductivity; RCC, relative chlorophyll content; WHC, water holding capacity

INTRODUCTION

Black soldier fly (*Hermetia illucens*) larvae (BSFL) are highly efficient decomposers [1]. Insect producers use side streams from other industries, such as restaurants and brewery waste, as feed for the larvae, which is converted into a high protein product during larval digestion [2]. By reusing food sources and recycling nutrients to create a high protein feed for other livestock, producers are reducing food costs and closing gaps in a circular economy [3]. Additionally, during the mass industrial rearing of insects, frass is produced in large quantities. Rather than allowing the frass to accumulate as waste, there is a growing interest in recycling these nutrients as horticultural amendments [4]. This has positive economic and environmental benefits for farmers and producers [5] and improves nutrient redirection in the food system [3].

BSFL frass has been studied in controlled environment agriculture (CEA) crops such as tomatoes [6,7], peppers [8], leafy greens [7,9–11], and sweet potatoes [12,13]. In most vegetable studies, low rates of frass incorporation have positive or neutral impacts on crop production and quality, while high rates of incorporation can produce negative outcomes for crop production. The seedling emergence of tomatoes, lettuce, and arugula has also been evaluated with frass treatments, indicating that frass in low concentrations can be effective as an amendment in starting media [14]. CEA includes the production of plants in structures such as high tunnels, greenhouses, growth chambers, or warehouses for indoor vertical farming [15]. CEA provides an alternative approach for food production with protection from natural environmental factors such as pests, disease, and extreme weather events. Greenhouses are also popular in urban areas with less land for crop production [16]. Recently, the number of US greenhouse producers has increased by 71%, and these numbers are expected to increase in the future [17].

Ornamental plants are commonly grown in CEA using soilless substrates often comprised of a high percentage of peat. Peat is an ideal substrate for crop growth due to its water holding capacity (WHC) and loamy texture and is common in greenhouse and gardening operations [15]. Additionally, as popularity of CEA increases, the use of peat-based substrates is increasing as well, and peatlands have been decreasing by 0.05% globally each year [18]. Peat is found in marsh environments, including decaying organic and inorganic components [19,20], and unfortunately, peat mining can result in biodiversity loss and greenhouse gas emissions [21,22]. Mined peat marshes experience disturbances to their methanotrophic bacteria, which are capable of filtering methane. When that filter is broken, peat marshes begin to emit methane into the atmosphere, increasing air pollution and greenhouse gas emission [23]. Wildlife diversity and richness also see significant reductions after peat mining occurs [24]. Furthermore, peat moss has also been increasing in price [25]. Therefore, alternatives to peat are a growing interest for ornamental producers [26].

In an effort to reduce reliance on peat for ornamental production, a few studies have investigated frass as a fertility amendment and alternative substrate. Mealworm (*Tenebrio molitor*) frass (MWF) and hen (*Gallus gallus domesticus*) manure were mixed into a growing mix to form two separate treatments for nasturtiums (*Tropaeolum majus*), zinnias (*Zinnia elegans*), and dwarf sunflowers (*Helianthus gracilentus*) and were compared to a control without MWF or hen manure [27]. Flowers per unit of all varieties, height and flower diameter of the dwarf sunflower, and overall biomass of nasturtium were significantly higher in the hen manure and MWF treatments compared to the control. Since manure is a common organic fertilizer, the lack of statistical significance indicates that insect frass can produce comparable results to an already adopted practice. The presence of some detritivores, like BSFL, can also reduce volatile organic compounds [28] and pest presence [29] in waste streams. Therefore, this is promising for the inclusion of frass in organic operations.

A study by Beasley et al. (2023) [30] utilized a conventional fertilizer control to provide more insight into the ability of frass to replace inorganic, chemical fertilizers in ornamental production. Coleus (*Plectranthus scutellarioides*) plants were grown in containers with increasing rates (0, 0.1, 0.2, and 0.3 kg/m^3 N) of standard fertilizer (SF) and BSFL frass fertilizer. Shoot dry weight was significantly higher in the 0.3 SF treatment compared to the 0.3 BSFL. At all other rates, SF and BSFL were statistically comparable. However, cumulative nitrogen leaching was significantly lower in the BSFL treatment compared to the SF. This indicates that an organic side stream, such as frass, can not only match synthetic fertilizers performance, but may also reduce negative environmental consequences, such as nutrient runoff. Other studies have utilized insect frass in evaluating flowering plants, herbivory, and pest survival [31,32]. Results from these studies indicate that flower number increases in black mustard, regardless of herbivore activity [31], and field mustard pest populations decreased with BSFL frass treatments [32].

Marigolds (*Tagetes*) are a genus of angiosperms native to North and Central America. While they are aesthetically and olfactorily pleasing for garden and landscaping design, they also have a large variety of cultural, medicinal, anti-pathogenic, and food related uses [33]. To our knowledge, insect frass has not been thoroughly investigated for marigold production; however, other studies have observed alternative peat replacements in marigold production. For example, vermicompost was incorporated into a potting medium for African Marigold (*Tagetes erecta*) at 10, 20, 30, 40, 50 and 60% [34]. The 60% treatment produced the highest fresh and dry weight of the shoots and roots, while also producing the greatest number of florets and photosynthetic pigments.

The objective of this study was to explore the impact of insect frass as a partial replacement of peat based potting mixes on the floral and plant growth characteristics of African marigolds (*Tagetes erecta* var. 'Inca II' Hybrid Color Mix) (Figure 1). Additionally, we wanted to examine the physical components, water holding capacity (WHC) and porosity, of insect frass when amended into peat based potting mixes. We hypothesize that growth and flowering parameters of marigolds grown in BSFL will be comparable to those grown in a 100% potting mix control. We also hypothesize that frass-based treatments will have higher or equal WHC and porosity compared to a 100% peat-based potting mix control.

Figure 1. African marigolds (*Tagetes erecta* var. 'Inca II' Hybrid Color Mix) grown in a peat-based potting mix amended with increasing ratios of black soldier fly larvae (BSFL) frass from left to right: 0% (white tag), 10% (yellow tag), 20% (green tag), and 40% (blue tag).

MATERIALS AND METHODS

The experiment took place in Denver, CO, USA at the Colorado State University Spur Terra greenhouse, elevation 1684.02 m (en-us.topographic-map.com). Greenhouse temperature and relative humidity set points were 17–25 °C and 40–75%, respectively. African marigold ‘Inca II’ (Park Seed Wholesale, Greenwood, SC, USA) seedlings were sown on September 21, 2023 in 84-cell trays in a peat-vermiculite germination mix (Lambert LM-GPS, Rivière-Ouelle, QC, Canada). They were watered once to twice a day, as needed. Seedlings were transplanted into 500 mL pots on October 27, 2023, in treatment mixtures consisting of a combination of peat mix [Berger BM6 peat blend (Saint-Modeste, QC, Canada)] and BSFL frass, reared mostly on spent brewery grains (EVO Conversion Systems, College Station, TX, USA) (Table 1).

Table 1. Compost analysis of BSFL frass, Berger BM6 Technical Data, and Tower Farms Dry Mineral Blend Fertilizer composition.

Parameter	Frass Dry Bases	Peat Mix (Range)	Fertilizer
pH	6.4	5.4–6.2	-
Ammonium (%)	8.6	0–0.002	1.3
Nitrate (%)	<0.001	0.003–0.0086	21.7
Phosphorus as P_2O_5 (%)	41.2	4–24	8
Potassium as K_2O (%)	22	0.0030–0.0098	38
Total Carbon (%)	46	-	-
Sulfur (%)	8.6	-	-
Calcium (%)	5.8	0.0072–0.019	19
Magnesium (%)	7.2	0.0023–0.0061	-
Sodium (%)	21.4	-	-
Zinc (ppm)	0.21	0.1–0.9	-
Iron (ppm)	0.6	0.5–2.2	-
Manganese (ppm)	0.11	0.2–1.1	-
Copper (ppm)	0.04	0–0.3	-
Boron (ppm)	0.006	0.05–0.44	-

The experiment was a completely randomized design (CRD) using four levels total, three treatments of each frass amended potting mixture and a 100% peat control (Table 2), with eight replicates per treatment.

Table 2. Marigolds were grown in BSFL frass treatment summary for 2023 greenhouse study. Treatments consisted of 100% Potting Mix Control (CPM 100%), and BSFL frass amended treatment (*v*:*v*) by percentage. Nitrogen content of each treatment was calculated using the average range values found in the peat and described in (Table 1).

Treatment	Peat (%)	Peat (cm^3)	BSFL (%)	BSFL (cm^3)	Nitrogen (%)
BSFL 40%	60	300	40	200	5.48
BSFL 20%	80	400	20	100	1.73
BSFL 10%	90	450	10	50	0.87
CPM 100%	100	500	0	0	0.0068

All treatments were watered once to twice a day and fertigated weekly with Tower Farms Dry Mineral Blend Fertilizer (Tower Garden LLC, Collierville, TN, USA), chemical composition (Table 1). Data collection for all treatments occurred on December 19, 2023. Plant size at harvest (PSH) was calculated by measuring plant width [the greatest width (W1) and the perpendicular width (W2); cm] and height (cm) using Equation (1) [10]:

$$PSH = \frac{W1 + W2 + H}{3} \tag{1}$$

Stomatal conductance (SC) was measured with a SC-1 Leaf Porometer System (Meter Group, Pullman, WA, USA) and relative chlorophyll concentrations (RCC) were taken with a handheld meter (atLEAF CHLBLUE, Wilmington, DE, USA) before harvest. atLeaf values were converted to SPAD and then mg/cm^2 using the conversion tool on the atLeaf website (https://www.atleaf.com/SPAD). Fully opened flowers and non-bloomed flowers, or florets, were counted to record floret number. Total relative flavonoid and anthocyanin concentrations were measured from fully opened flowers with an MPM-100 multipigment reader (Opti-Sciences, Hudson, NM, USA). Fully opened flowers were separated from the rest of the plant, placed in paper bags, and dried in a Heratherm drying oven (Thermo Fisher Scientific, Waltham, MA, USA) separately from the rest of the plant at 60^{O}C Both flower and plant dry matter were weighed after 72 h in the drying oven (Mettler Toledo, Denver, CO, USA).

Post destructive harvest, electrical conductivity (EC) and pH measurements were taken using the pour through method [35] on December 22, 2023. The pots were irrigated as usual and drained for a minimum of 30 min. A volume of 100 mL of distilled water was poured into each pot and let to drain in a glass beaker, where the leachate was collected. The leachate was then measured with a pH/EC combo meter (Bluelab Corporation, Industrial Park, Tauranga, New Zealand).

Further, water holding capacity (WHC) and porosity of the substrate treatments were evaluated on December 1, 2023, separately from the main experiment. This evaluation followed a CRD, similar to Table 2, but included the 100% frass control to fully evaluate the design, producing five levels total and four replicates per treatment. Treatments were mixed, placed in paper bags, and dried in a drying oven for 72 h at 70 °C. On December 4, 2023, dried substrates were weighed and placed in 500 mL pots. 150 mL of distilled water was slowly poured through each treatment and drained into plastic beakers and allowed to drip for approximately two minutes. Pour through liquid was measured and the wet substrates were left to sit in 3.8 L buckets. On December 6, 2023, 48 h later, saturated treatments were weighed. WHC and porosity were calculated with Equations (2) and (3), respectively:

$$WHC\ (\%) = \frac{Saturated\ weight(g) - Dry\ wieght(g)}{Dry\ weight(g)} \times 100 \tag{2}$$

$$Porosity\ (\%) = \frac{Volume\ pourthrough\ liquid\ (mL) + Volume\ solid(mL)}{Volume\ pourthrough\ liquid(mL)} \times 100 \tag{3}$$

Statistical analysis was conducted using JMP®, Pro 17 (SAS Institute Inc., Cary, NC, 1989–2023, USA) and R Studio (Boston, MA, USA) 2025.05.1 (R version 4.4.2). To evaluate water holding capacity and porosity, percentages were converted into proportions and transformed with a logit transformation. The Anderson-Darling test for normality and Levene's test for equal variance were conducted to determine if the assumptions for an ANOVA were met. A one-way ANOVA was used to analyze the differences between treatments and were followed by a post hoc Tukey's HD multiple comparison test when appropriate. A threshold of $p < 0.05$ was significant.

Because differences in flower color among plants were not evident at the beginning of the experiment, a flower color metric was incorporated into the analysis to account for these differences as flower development occurred. A color value was assigned to each plant to quantify variation in *yellow* intensity. This color metric was included as a covariate to explain a portion of the variability among plants pertaining to flower color and to isolate, as much as possible, the effects of the treatments.

The analysis of covariance was performed in SAS 9.4 using proc GLIMMIX for the following variables: PHS, PDW, EC, pH, SC, SPAD, FDW, FLORET (under the assumption that this response follows the Poisson distribution), FLAV, and ANTH. Mean separation was conducted through the postprocessing procedure PLM, with Tukey's method used to control for multiplicity at the 5% significance level. Depending on the Bayesian Information Criterion (BIC) metric, that evaluates model fit, the covariate effect was either made treatment specific or only entered the model as a main effect.

RESULTS

Plant Growth Characteristics

Plant size at harvest (Figure 2A) and plant dry weight (Figure 2B) were greatest in the control and BSFL 10% treatment and lowest in the BSFL 40% treatment ($F = 50.30$; $p < 0.0001$, $F = 55.56$; $p < 0.0001$). Relative chlorophyll concentration (Figure 2C) was significantly higher in the BSFL 10% and lowest in the BSFL 40% ($F = 4.20$; $p = 0.01$). Stomatal conductance (Figure 2D) in the BSFL 20% treatment was significantly higher than the control and BSFL 40% ($F = 8.50$; $p = 0.0004$).

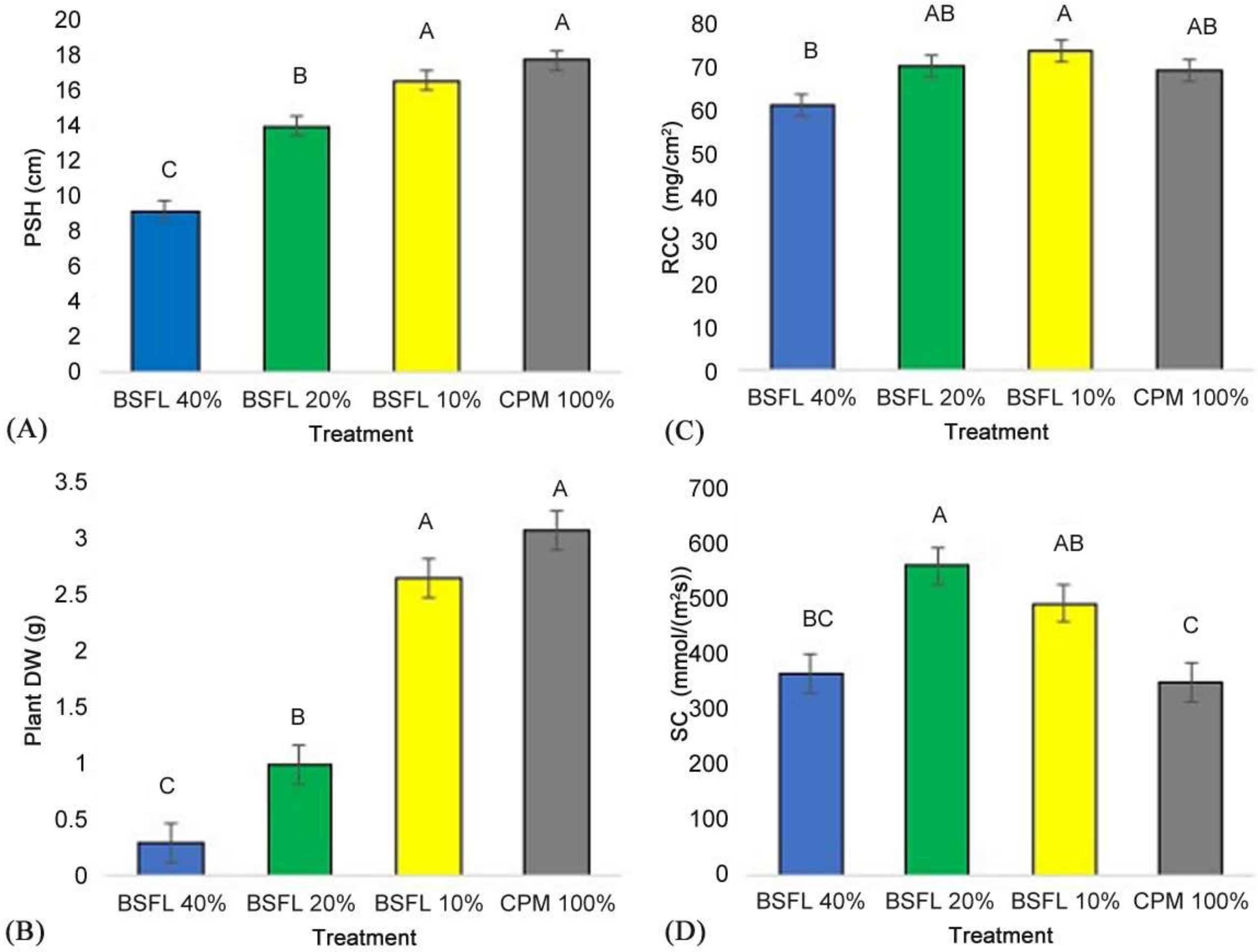

Figure 2. Plant Size at Harvest (PSH) (**A**), Plant Dry Weight (DW) (**B**), Relative Chlorophyll Concentrations (RCC) (**C**), and Stomatal Conductance (SC) (**D**) ±SEM of marigolds grown in BSFL frass. Marigolds were grown in a 100% potting mix control (CPM 100%: grey column) and three treatments with BSFL frass in partial peat replacements (BSFL 10% treatment: yellow columns, BSFL 20%: green columns, and BSFL 40%: blue columns). Different letters (A–C) indicate significant differences between treatments ($\alpha = 0.05$), ANOVA followed by Tukey's HSD.

Floral Characteristics

The flower response variables were only evaluated for treatments where flowering occurred: CPM 100%, BSFL 10%, and BSFL 20%. Dry weight of the marigold flower (Figure 3A) and floret number (Figure 3B) was greater in the BSFL 10% treatment and control compared to the BSFL 20% treatment ($F = 8.09$; $p = 0.0025$, $F = 12.42$; $p \leq 0.0001$). Differences in relative flavonoid ($F = 1.22$; $p = 0.31$) and anthocyanin ($F = 1.51$; $p = 0.24$) concentrations (Figures 3C,D) were not statistically significant between treatments and/or control.

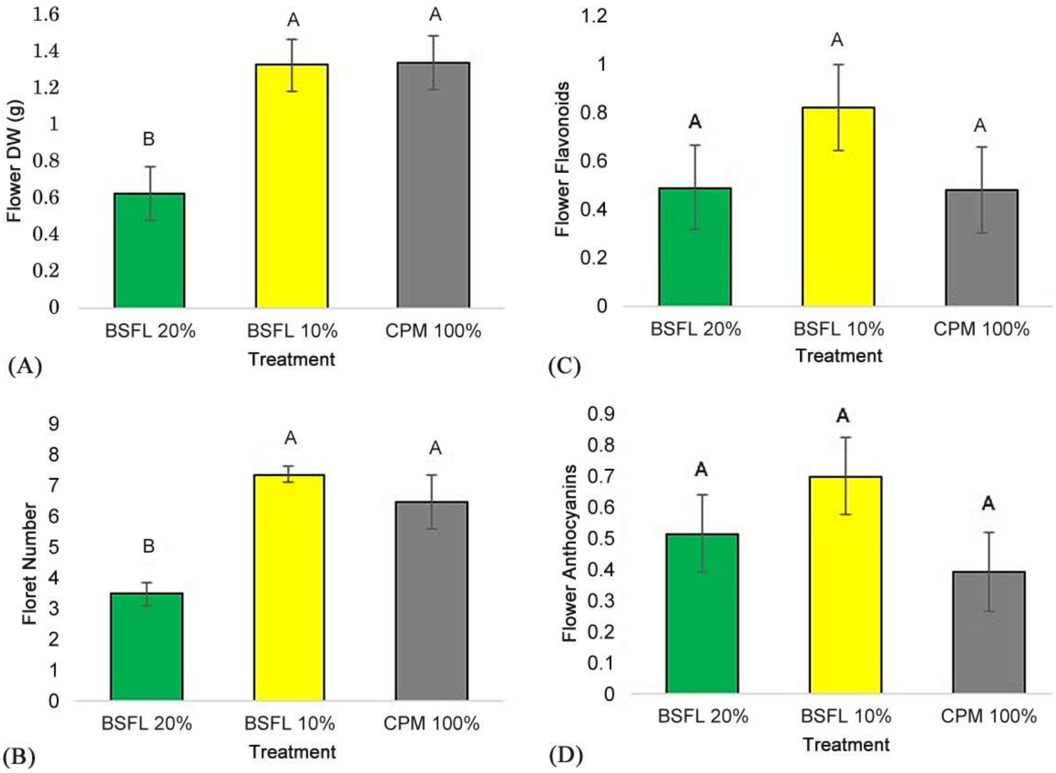

Figure 3. Flower Dry Weight (DW) (**A**), Floret Number (**B**), and Relative Flavonoid (**C**) and Anthocyanin Concentrations (**D**) ±SEM of marigolds grown in BSFL frass. Marigolds were grown in a 100% potting mix control (CPM 100%: grey column) and three treatments with BSFL frass in partial peat replacements (BSFL 10% treatment: yellow columns and BSFL 20%: green columns). Different letters (A–B) indicate significant differences between treatments (α = 0.05), ANOVA followed by Tukey's HSD.

Flower Color

The African Marigold variety 'Inca II' was selected for this experiment. While the variety is stated to be uniform in height, habit, and bloom size, the seed utilized included a mix of flower colors. While seed mixes such as this are commonly used in commercial production, flower color can be an indicator of additional variation in plant phenotype. To ensure that flower color was the only trait showing inherent variation in the present experiment, an additional analysis of flower color was conducted for each parameter. Treatments resulting in flower development were evaluated, with flower color as a covariate in an ANCOVA analysis (Table 3). The importance of the interaction term was evaluated based on a model-fit criterion (BIC) which determined whether to retain or remove it. Flower color was only significant in the floral relative anthocyanin concentrations (Table 3), whereby an increase in anthocyanin concentrations was observed for orange flowers compared to yellow flowers, but gold flowers were statistically comparable to both yellow and orange flowers. For the parameters where flower color and treatment interaction were analyzed, there were no significant interaction effects. Of note is the effects of treatment were not of interest for further discussion as this analysis only included the treatments where flowering occurred, and not the BSFL 40%.

Table 3. ANCOVA results including treatment (T), flower color (C), and treatment by flower color interaction (T*C) in the model. The importance of the interaction term was evaluated based on a model-fit criterion (BIC) which determined whether to retain or remove it.

	F values			P values		
Parameter	**Treatment**	**Color**	**T*C**	**Treatment**	**Color**	**T*C**
ph	1.06	0.14	-	0.38	0.71	-
EC	5.68	1.11	-	0.02	0.32	-
PSH	5.16	0.12	2.28	0.02	0.73	0.14
Plant DW	7.2	0.2	0.46	0.02	0.65	0.65
SC	6.17	0.82	-	0.01	0.38	-
RCC	0.55	0.00	-	0.59	0.99	-
Flower DW	11.67	0.00	-	0.0007	0.99	-
Floret Number	3.97	0.28	-	0.04	0.60	-
Flavonoids	1.76	2.18	1.66	0.23	0.17	0.26
Anthocyanins	0.58	9.55	-	0.58	0.01	-

Potting Mix Chemical Components

EC (Figure 4A) after the study was completed was highest in the BSFL 40% leachate, then BSFL 20%, and lowest in the BSFL 10% and control (F = 51.98; p ≤ 0.0001). The opposite trend occurred for pH (Figure 4B), where BSFL 40% was significantly lower than BSFL 10% (F = 3.18; p = 0.04).

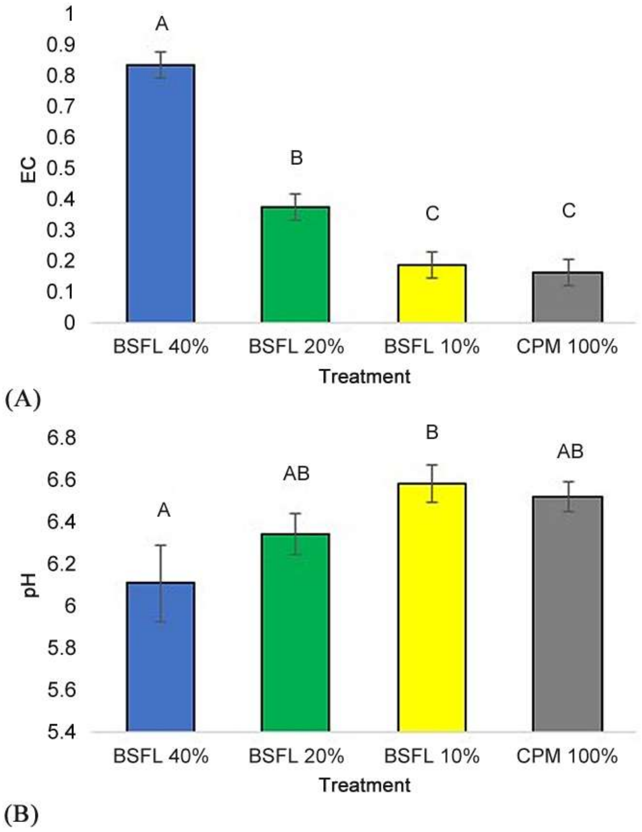

Figure 4. Electrical Conductivity (EC) (**A**), and pH (**B**) ± SEM of BSFL frass amended potting mix. Marigolds were grown in a 100% potting mix control (CPM 100%: grey column) and three treatments with BSFL frass in partial peat replacements (BSFL 10% treatment: yellow columns, BSFL 20%: green columns, and BSFL 40%: blue columns). Different letters (A–C) indicate significant differences between treatments (α = 0.05), ANOVA followed by Tukey's HSD.

Potting Mix Physical Components

There were no significant differences in WHC (Figure 5A) or percent porosity (Figure 5B) between treatment means (F = 0.50; p = 0.74, F = 1.44; p = 0.27).

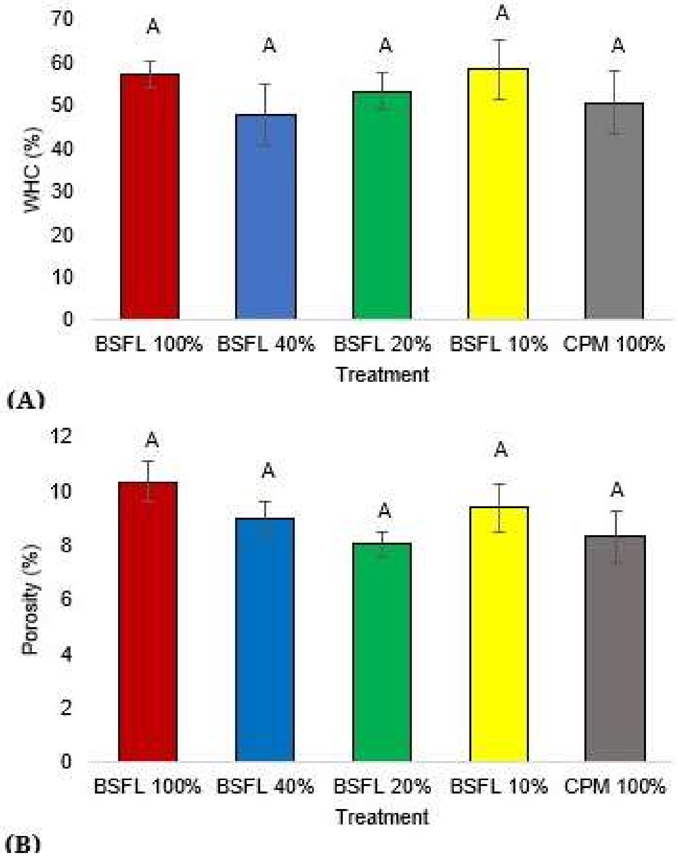

Figure 5. Water holding capacity (WHC) (in percentage) (**A**) and porosity (**B**) (in percentage) ± SEM of BSFL frass treatments. WHC was tested in a 100% potting mix control (CPM 100%: grey column), a 100% frass control (BSFL 100%: red column), and three treatments with BSFL frass in partial peat based potting mix replacements (BSFL 10% treatment: yellow columns, BSFL 20%: green columns, and BSFL 40%: blue columns). Letter (A) indicates no significant differences between treatments and controls (α = 0.05).

DISCUSSION

The BSFL 10% treatment was comparable to the control in all parameters, except stomatal conductance (SC). This indicates that low amounts of frass incorporation can have positive or neutral results for ornamental growth and production, similar to what has been seen in food crops [6,7,9,10]. Benefit cost analysis of sweet potato slips grown in BSFL frass reduced operation costs by one to two thousand dollars a year [12]. Over time these reductions could possibly accumulate into savings, while also reducing the harmful consequences of peat extraction, resulting in a more circular economy [3] for insect producers and ornamental plant growers.

Reduced PSH observed in the higher frass treatments (BSFL 40%) may have been due to several factors including higher concentrations of soluble salts, ammonium toxicity, or the effects of microbes. For soluble salts, sodium (Na) was observed in high concentrations through the frass analysis (Table 2). Additionally, EC was highest in the BSFL 40% treatment leachate at the end of the study. Increases in Na uptake [9,10] and EC [36] with frass applications have been reported in several vegetable studies and are known to produce harmful outcomes for plant growth, like reduced plant size, weight, and, in high enough concentrations, reduce survival [37]. Additionally, the higher proportion of nitrogen present as ammonium in the frass analysis (Table 1) possibly reduced plant dry weight, as excessive ammonium has been shown to limit marigold growth [38]. Specifically, marigold height, fresh weight and dry weight were found to be highest when nitrate and ammonium were balanced (50/50) in the fertilizer applied. Higher proportions of ammonium reduced marigold dry weight significantly [39]. Increased ammonium concentrations relative to nitrates were observed in frass derived from food waste [40]. This has also been identified as a potential issue in other frass treated studies, correlating with decreased spring onion and sweet corn growth [41]. Additionally, studies indicate that BSFL fed varying diets produced the highest soil nitrate and ammonium in a high protein and N diet [42]. This was also connected to higher CO_2, N_2O, and NO fluxes in soils, which could lead to an increase in greenhouse gas emissions. Microbially, the high carbon content of frass may lead to high biological oxygen demand resulting in low oxygen conditions in the root zone and potential nitrogen immobilization, which can negatively affect plant growth [39]. Though marigolds are known for their anti-pathogenic compounds and bioremedial properties [43], several microoganisms are known to negatively impact marigold production, such as Cucumber mosaic virus (*Cucumovirus CMV*) [44] and black spot (*Alternaria sp.*) [45]. These can be introduced to marigolds through sap [44], wind, water, or direct contact, and can be exacerbated by weather conditions [45]. Additionally, bacterial abundance and diversity may increase in frass treated substrates compared to those treated with conventional urea fertilizers [46], which could have negative or positive outcomes for marigold growth and production. Ultimately, while frass introduction into a greenhouse substrate may alter the plant microbiome, further research isolating individual microorganisms and their interaction with the plant is needed, especially when pathogens have been identified as a concern in the prospective crop selection.

Lack of significant differences pertaining to the physical properties of the treatments, WHC and porosity, further informs the inference that chemical, microbial, or a combination of these factors may be the cause of negative plant outcomes at high percentages of frass inclusion. It is also important to note that the WHC analysis was conducted with fresh media and frass containing no plant material. Thus, it is possible that longer term effects and interactions may occur over the course of crop production in a greenhouse [39]. Interactions with the root system, irrigation, and fertilizer applications will likely impact WHC throughout the duration of both the plant and frass life span. Therefore, future studies should include a WHC analysis conducted throughout the duration of the experiment and at the end. Additionally, SC was lowest in the control and highest in the BSFL 20% treatment. This result differs from the trend observed in the other parameters, but may be due to increased water availability, which generally results in increased water use [47]. The BSFL 40% treatment, highest in EC, did not flower and produced the smallest plants. While the lack of growth observed in this treatment may have led to reduced SC, the high Na observed in the frass may also have led to salt stress resulting in a reduced SC (Table 1). The presence of high salt concentration resulting in stress is further indicated by higher EC observed in the BSFL 40% leachate (Figure 4). Based on PSH and dry weight results, the BSFL 20% treatment also appears to be a frass incorporation rate high enough to induce stress and reduce plant productivity and flowering, albeit not as detrimental as BSFL 40%. However, the BSFL 20% treatment resulted in the highest SC observed in this study. This increase in SC may also be a response to salinity stress, which has been observed in iceberg lettuce (*Lactuca sativa* var. Capitata)) through a decrease plant water use efficiency [48] as well as an increase in stomatal opening in tomatoes (*Solanum lycopersicum* var 'Capello') [49].

Despite frass having a higher pH than the peat, the BSFL 40% treatment leachate had the lowest pH. This is likely due to the poor root system (and overall growth) of the plants in this treatment and the subsequent decrease in fertilizer uptake, which was primarily composed of nitrates (Table 1). Nitrate uptake by plants increases pH over time as the plants release OH into the substrate. Therefore, actively growing plants should experience an upward trend in pH, whereas poorly developed plants, would produce a lower pH environment in comparison. Ammonium uptake by plants conversely releases H+ into the substrate. Over time, the high ammonium present in the frass is also likely contributing to a reduced pH in high frass treatments [50].

Given frass has the physical attributes, as they pertain to porosity and WHC at the start of the study, to promote plant growth, adjustments can be made to mitigate other issues. Coconut coir has become a common component in many greenhouse substrates. However, due to its high concentration of sodium, the material must be pretreated. Washing coconut coir before incorporation has become an effective and common practice for producers and consumers [51]. A study utilizing BSFL frass amendments in ornamental production included a similar washed treatment to reduce initial sodium concentrations. This treatment reduced peat inclusion by 40% and produced results statistically comparable to the control in plant size, shoot weight, root weight, flower weight, and chlorophyll concentrations [52]. Treatments (chemical, physical, or thermal) prior to frass application may also change microbial interactions in the potting mix. For example, frass is commonly heat treated after digestion to reduce foodborne pathogens, such as *Salmonella* [53]. This also emphasizes the importance of the larval diet, which has been observed to impact the microbial communities present in frass [54]. Altering larval diet has also been an effective way of reducing ammonium toxicity in frass treated plants [55] and studies with low initial concentrations of ammonium in the frass produced leachate samples that did not contain ammonium [10]. Thus, exploring methods to reduce ammonium post rearing is another area of future research. Pre-treating the frass prior to incorporation could allow for greater percentages to be introduced in potting mixes, further reducing costs and concerning environmental practices.

Quality parameters, such as relative flavonoid and anthocyanin concentrations of the flower petals, were statistically comparable across all treatments and the control. In contrast, kale (*Brassica oleracea* cv. Blue ridge) grown in a peat-based substrate amended with 60% and 40% BSFL frass produced significantly higher concentrations of flavonoids compared to the 100% peat control [56]. Thus, the impact of BSFL frass on plant quality parameters may be species specific. Flavonoid concentrations in the diet of insects have been seen to increase the flavonoid concentrations in the resulting frass [57], further emphasizing the importance of larval diet management in insect production. Flavonoids are secondary metabolites associated with producing positive health outcomes for humans [58]. Similar studies observed increased anthocyanin concentration in red cabbage (*Brassica oleracea*) microgreens when plants were fertilized with insect frass [59]. The larvae were reared on a diet of both brewery grains and okra, further supporting that larvae diet may impact crop results from frass incorporation. Anthocyanins are plant antioxidants that can serve a variety of purposes including dyes and medicines [60]. Due to the pigmented nature of the compound, it is reasonable to expect results would vary with the varying marigold flower colors utilized in the present study and that fewer treatment effects would be observed. Since marigolds are often grown for medicinal purposes [33], the lack of differences between treatments and control in relative flavonoid and anthocyanin concentrations is promising for frass utilization, especially at the 10% incorporation rate, since the flower dry weight was also comparable to the control. Increasing antioxidants in food and medicinal crops may be important for future research to increase human health outcomes [61]. This may be especially beneficial if sourced from insect frass, as it may also improve agricultural sustainability and resiliency [62]. Additionally, each plant in this study produced one full flower and several florets, or unbloomed flowers. Floret number was also highest in BSFL 10% treatment, possible providing further incentive for the incorporation of frass into substrate mixes for commercial production.

Marigolds have been a large component of the floriculture industry for decades, especially across Asia [63]. 600,000 tons of marigolds are produced globally each year, approximately 75–80% by India, 80% of which is consumed locally [43]. In India, marigolds and most other crops are grown outdoors. Due to the high initial costs, only 5000 ha is currently operating as CEA in the country [64]. Interestingly, studies have observed significant increase in marigold height, weight, yield, and flower number when grown in a controlled environment compared to a conventional outdoor system [65]. Incorporating frass into CEA substrates presents a valuable opportunity to reduce both peat and synthetic fertilizers. Ultimately, redirecting waste streams from one cycle of production to another (Figure 6) can decrease material sent to the landfill, prevent natural resource extraction, protect vulnerable ecosystems [66], and improve circular economies [3].

Figure 6. The circular economy relationship for insect producers, crop growers, and consumers. Insect producers use food waste to feed larvae and create a high protein product. Leftover frass can be utilized as a horticultural fertilizer or amendment during crop production. Crop growers sell or donate their products to other food partners, such as restaurants and grocery stores.

CONCLUSIONS

This study indicates that there is no impact on ornamental production or chemistry in a marigold color mix at a 10% BSFL frass incorporation. Therefore, without any treatment prior to incorporation, frass can replace 10% of a peat-based substrate without negatively impacting quality factors such as flower yield and antioxidants, which are the parameters of most interest to ornamental and medicinal producers. Additionally, plant size, weight, and greenness are not affected at a 10% incorporation rate. Future studies interested in evaluating commercially relevant cultivar mixes should run a color spectrum analysis to numerically quantify flower-color differences. Such information can then be used as a covariate whenever there is reason to suspect that flower coloration reflects physiological or experimental-unit differences. This creates opportunities to incorporate frass into commercial CEA production and to further increase research efforts to fully explore the impact of industry side streams on ornamental crops. Furthermore, frass amendments may help reduce the use of peat in an industry that relies on it heavily, but future research is needed to examine treatment methods for reducing salinity and ammonium stress.

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

Conceptualization, MYC; methodology, MYC, JH; formal analysis, MYC, CV-C; investigation, MYC, JH; resources, JH, JKC, JB; data curation, MYC; writing—original draft preparation, MYC; writing—review and editing, MYC, JH, JKC, JB, CV-C; visualization, MYC; project administration, JKC, JB; funding acquisition, JKC, JB. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

FUNDING

This research was funded by Colorado State University Spur.

ACKNOWLEDGMENTS

Great thanks to Rebekah Buena for her assistance in data collection and watering. Thank you to CSU Spur Soil, Water, and Plant Testing Lab in Denver, CO for completing our frass analysis.

REFERENCES

1. Miranda CD, Cammack JA, Tomberlin JK. Life-history traits of the black soldier fly, *Hermetia illucens* (L.)(Diptera: Stratiomyidae), reared on three manure types. Animals. 2019;9(5):281. doi: 10.3390/ani9050281
2. Diener S, Zurbrügg C, Tockner K. Conversion of organic material by black soldier fly larvae: establishing optimal feeding rates. Waste Manag Res. 2009;27(6):603-10. doi: 10.1177/0734242X09103838
3. Chavez M. The sustainability of industrial insect mass rearing for food and feed production: zero waste goals through by-product utilization. Curr Opin Insect Sci. 2021;48:44-9. doi: 10.1016/j.cois.2021.09.003
4. Schmitt E, de Vries W. Potential benefits of using *Hermetia illucens* frass as a soil amendment on food production and for environmental impact reduction. Curr Opin Green Sustain Chem. 2020;25:100335. doi: 10.1016/j.cogsc.2020.03.005
5. Yudiarini N, Sulit MF. Maggot Frass Fertilizer: Effects on Productivity and Economic Efficiency in Organic Vegetable Farming. Agro Bali: Agric J. 2025;8(3):953-61. doi: 10.37637/ab.v8i3.2453

6. Chavez MY, Uchanski M, Tomberlin JK. Impacts of black soldier fly, (Diptera: Stratiomyidae) larval frass on tomato production. J Econ Entomol. 2023;116(5):1490-5. doi: 10.1093/jee/toad150
7. Setti L, Francia E, Pulvirenti A, Gigliano S, Zaccardelli M, Pane C, et al. Use of black soldier fly (Hermetia illucens (L.), Diptera: Stratiomyidae) larvae processing residue in peat-based growing media. Waste Manag. 2019;95:278-88. doi: 10.1016/j.wasman.2019.06.017
8. Romano N, Powell A, Islam S, Fischer H, Renukdas N, Sinha AK, et al. Supplementing aquaponics with black soldier fly (*Hermetia illucens*) larvae frass tea: Effects on the production and composition of sweetpotato slips and sweet banana peppers. Aquaculture. 2022;555:738160. doi: 10.1016/j.aquaculture.2022.738160
9. Chavez MY, Uchanski M, Tomberlin JK. Impacts of black soldier fly, Hermetia illucens, larval frass on lettuce and arugula production. Front Sustain Food Syst. 2024;8:1399932. doi: 10.3389/fsufs.2024.1399932
10. Chavez MY, Villa Ignacio A, Craver JK, Bousselot J. Investigating Black Soldier Fly Larval (*Hermetia illucens*) Frass Applications as a Partial Peat Replacement and Liquid Fertilizer in Brassicaceae Crop Production. Agrochemicals. 2025;4(2):8. doi: 10.3390/agrochemicals4020008
11. Romano N, Datta SN, Sinha AK, Pande GS. Partially replacing synthetic fertilizer with black soldier fly (Hermetia illucens) larvae frass enhances kale (*Brassica oleracea* var. *sabellica*) production. Technol. Hortic. 2023;3:8. doi: 10.48130/TIH-2023-0008
12. Romano N, Fischer H, Powell A, Sinha AK, Islam S, Deb U, et al. Applications of black solider fly (*Hermetia illucens*) larvae frass on sweetpotato slip production, mineral content and benefit-cost analysis. Agronomy. 2022;12(4):928. doi: 10.3390/agronomy12040928
13. Romano N, Webster C, Datta SN, Pande GSJ, Fischer H, Sinha AK, et al. Black soldier fly (*Hermetia illucens*) frass on sweet-potato (Ipomea batatas) slip production with aquaponics. Horticulturae. 2023;9(10):1088. doi: 10.3390/horticulturae9101088
14. Chavez MY, Uchanski M, Tomberlin JK. Impacts of black soldier fly, Hermetia illucens, larval frass on the emergence and seedling vigor of three vegetable crop species. J Insects Food Feed. 2024;1:819-32. doi: 10.1163/23524588-00001263
15. Niu G, Masabni J. Plant production in controlled environments. Horticulturae. 2018;4(4):28. doi: 10.3390/horticulturae4040028
16. Walker SJ, Dickerson GW, Joukhadar I. Greenhouse Vegetable Production. Las Cruces (NM, US): NMSU College of Agricultural Consumer and Environmental Sciences Extension Publication; 2019.
17. Maureira F, Stöckle CO, Rajagopalan K. Greenhouse Production of Vegetables: Implications for the Regional Food-Energy-Water System. In: Food-Energy-Water: Innovations in Storage for Resilience in the Columbia River Basin. Progress Report for the Columbia River FEW Project. Available from: https://wpcdn.web.wsu.edu/wp-wpsites/uploads/sites/1428/2019/12/2019-FINAL-Columbia-FEW-Progress-Report.pdf. Accessed on 2025 Nov 1.

18. Brioche A. Peat data sheet. U.S. Geological Survey, Mineral Commodity Summaries. Available from: https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-peat.pdf. Accessed on 2025 Nov 1.
19. Bloom AL. Peat accumulation and compaction in a Connecticut coastal marsh. J Sediment Res. 1964:34(3):599-603. doi: 10.1306/74D710F5-2B21-11D7-8648000102C1865D
20. Cameron CC, Esterle JS, Palmer CA. The geology, botany and chemistry of selected peat-forming environments from temperate and tropical latitudes. Int J Coal Geol. 1989:12(1-4):105-56. doi: 10.1016/0166-5162(89)90049-9
21. Räsänen A, Albrecht E, Annala M, Aro L, Laine AM, Maanavilja L, Mustajoki J, Ronkanen AK, Silvan N, Tarvainen O, Tolvanen A. After-use of peat extraction sites–A systematic review of biodiversity, climate, hydrological and social impacts. Science Total Enviro. 2023;882:163583. doi: 10.1016/j.scitotenv.2023.163583
22. Hirschler O, Osterburg B, Weimar H, Glasenapp S, Ohmes MF. Peat replacement in horticultural growing media: Availability of bio-based alternative materials. Thünen Working Paper. Braunschweig (Germany): Johann Heinrich von Thünen-Institut (vTI); 2022. pp. 1-41. doi: 10.3220/WP1648727744000
23. Kaupper T, Mendes LW, Harnisz M, Krause SMB, Horn MA, Ho A. Recovery of methanotrophic activity is not reflected in the methane-driven interaction network after peat mining. Appl. Environ. Microbiol. 2021;87:e02355. doi: 10.1128/AEM.02355-20
24. Couwenberg J, Thiele A, Tanneberger F, Augustin J, Bärisch S, Dubovik D, Liashchynskaya N, Michaelis D, Minke M, Skuratovich A, et al. Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. Hydrobiologia. 2011:674:67-89. doi: 10.1007/ s10750-011-0729-x
25. Abad M, Noguera P, Bures S. National inventory of organic wastes for use as growing media for ornamental potted plant production: case study in Spain. Bio. Tech. 2001;77:197-200. doi: 10.1016/S0960-8524(00)00152-8
26. Fascella G. Growing Substrates Alternative to Peat for Ornamental Plants. In Soilless Culture: Use of Substrates for the Production of Quality Horticultural Crops. London (UK): InTechOpen. 2015. pp. 47-68. doi: 10.5772/59596
27. Hénault-Ethier L, Reid B, Hotte N, Paris N, Quinche M, Lachance C, et al. Growth trials on vegetables, herbs, and flowers using mealworm frass, chicken manure, and municipal compost. ACS Agric. Sci. Technol. 2023;3(3):249-59. doi: 10.1021/acsagscitech.2c00217
28. Beskin KV, Holcomb CD, Cammack JA, Crippen TL, Knap AH, Sweet ST, et al. Larval digestion of different manure types by the black soldier fly (*Diptera: Stratiomyidae*) impacts associated volatile emissions. Waste Manag. 2018;74:213-20. doi: 10.1016/j.wasman.2018.01.019
29. Bradley SW, Sheppard DC. House fly oviposition inhibition by larvae of *Hermetia illucens*, the black soldier fly. J Chem Ecol. 1984;10(6):853-9. doi: 10.1007/BF00987968

30. Beasley J, Kuehny J, Gentimis T, Fields J. Black soldier fly frass supports plant growth and reduces nitrogen leaching during coleus production. HortTechnology. 2023;33(3):305-12. doi: 10.21273/HORTTECH05093-22
31. Barragán-Fonseca KY, Rusman Q, Mertens D, Weldegergis BT, Peller J, Polder G, et al. Insect exuviae as soil amendment affect flower reflectance and increase flower production and plant volatile emission. Plant Cell Env. 2023;46(3):931-45. doi: 10.1111/pce.14516
32. Chia SY, van Loon JJ, Dicke M. Effects of frass from larvae of black soldier fly (*Hermetia illucens*) and yellow mealworm (*Tenebrio molitor*) on growth and insect resistance in field mustard (*Brassica rapa*): differences between insect species and frass treatments. Entomol Exp Appl. 2024;172(5):394-408. doi: 10.1111/eea.13425
33. Salehi B, Valussi M, Morais-Braga MFB, Carneiro JNP, Leal ALAB, Coutinho HDM, et al. Tagetes spp. essential oils and other extracts: Chemical characterization and biological activity. Molecules. 2018;23(11);2847. doi: 10.3390/molecules23112847
34. Sardoei AS, Roien A, Sadeghi T, Shahadadi F, Mokhtari TS. Effect of vermicompost on the growth and flowering of African Marigold (Tagetes erecta). Am-Eurasian J Agric Environ Sci. 2014;14:631-635. doi: 10.5829/idosi.aejaes.2014.14.07.12366
35. Camberato DM, Lopez RG, Mickelbart MV. Commercial Greenhouse Production: pH and electrical conductivity measurements in soilless substrates. West Lafayette (IN, US): Purdue University; 2009.
36. Zahn NH, Quilliam R. The effects of insect frass created by *Hermetia illucens* on spring onion growth and soil fertility. Sterling (Scotland): University of Sterling; 2017.
37. Kronzucker HJ. Coskun, D.; Schulze, L. M.; Wong, J. R.; Britto, D. T. Sodium as nutrient and toxicant. Plant Soil. 2013;369(1): 1-23. doi 10.1007/s11104-013-1801-2
38. Choi JM, Chung HJ. Influence of Pre-Plant Micronutrient Mixes and Ammonium to Nitrate Ratios in Fertilizer Solution on Growth and Micronutrient Contents of Marigold in Plug Culture. J Plant Nutr. 2007;30(6):915-26. doi: 10.1080/15226510701375440
39. Raviv M. Composts in Growing Media: Feedstocks, Composting Methods and Potential Applications. Acta Hortic. 2014;1018:513-23. doi: 10.17660/ActaHortic.2014.1018.56
40. Green TR, Popa R. Enhanced ammonia content in compost leachate processed by black soldier fly larvae. Appl Biochem Biotechnol. 2012;166(6):1381-7. doi: 10.1007/s12010-011-9530-6
41. Hénault-Ethier L, Quinche M, Reid B, Hotte N, Fortin A, Normandin É, Renaud GDLR, Zadeh AR, Deschamps MH, Vandenberg G. Opportunities and challenges in upcycling agri-food byproducts to generate insect manure(frass): A literature review. Waste Manag. 2024;176:169-191. doi: 10.1016/j.wasman.2023.12.033

42. Rummel PS, Beule L, Hemkemeyer M, Schwalb SA, Wichern F. Black soldier fly diet impacts soil greenhouse gas emissions from frass applied as fertilizer. Front Sustain Food Syst. 2021;5:709993. doi: 10.3389/fsufs.2021.709993
43. Singh Y, Gupta A, Kannojia P. Tagetes erecta (Marigold)-A review on its phytochemical and medicinal properties. Curr Med Drug Res. 2020;4(1):1-6. doi: 10.53517/CMDR.2581-5008.412020201
44. Sultana R, Akanda AM, Haque MA, Majumdar A, Munsur MA. An investigation to virus like diseases of marigold. J Biosci Agric Res. 2014;2(01):23-35. doi: 10.18801/jbar.020114.16
45. Cheng X, Lu YM, Chen DL, Luo C, Li MY, Huang CL. Pathogen and disease characteristics of marigold black spot in Beijing and surrounding areas. Plant Pathol. 2019;68(4):689-99. doi: 10.1111/ppa.12994
46. Nogalska A, Przemieniecki SW, Krzebietke SJ, Kosewska A, Załuski D, Kozera WJ, et al. Farmed insect frass as a future organic fertilizer. Appl Sci. 2024;14(6):2380. doi: 10.3390/app14062380
47. Al-Kaisi MM, Broner I. Crop water use and growth stages. Fort Collins (CO, USA): Colorado State University Extension; 2014.
48. Kurunc, A. Effects of water and salinity stresses on growth, yield, and water use of iceberg lettuce. J Sci Food Agric. 2021;101(13):5688-96. doi: 10.1002/jsfa.11223
49. Xu HL, Gauthier L, Gosselin A. Stomatal and cuticular transpiration of greenhouse tomato plants in response to high solution electrical conductivity and low soil water content. J Am Soc Hortic Sci. 1995;120(3):417-22. doi: 10.21273/JASHS.120.3.417
50. Johnson CN, Fisher PR, Huang J, Yeager TH, Obreza TA, Vetanovetz RP, et al. Effect of fertilizer potential acidity and nitrogen form on the pH response in a peat-based substrate with three floricultural species. Sci Hortic. 2013;162:135-43. doi: 10.1016/j.scienta.2013.08.001
51. Hussaini MM, Dhanapal S. Optimization of Coco Peat Processing for Salt Removal Efficiency and Environmental Sustainability. Available from: https://www.ijert.org/research/optimization-of-coco-peat-processing-for-salt-removal-efficiency-and-environmental-sustainability-IJERTCONV12IS03041.pdf. Accessed on 2026 Jan 8.
52. Chavez MY, Craver JK, Bousselot J. Investigating applications of black soldier fly larvae (Hermetia illucens) frass in ornamental horticultural production. Acta Hortic. Forthcoming 2026.
53. Van Looveren N, Vandeweyer D, Van Campenhout L. Impact of heat treatment on the microbiological quality of frass originating from black soldier fly larvae (*Hermetia illucens*). Insects. 2021;13(1):22. doi: 10.3390/insects13010022
54. Leite-Mondin M, DiLegge MJ, Manter DK, Weir TL, Silva-Filho MD, Vivanco JM. The gut microbiota composition of Trichoplusia ni is altered by diet and may influence its polyphagous behavior. Sci Rep. 2021;11(1):5786. doi: 10.1038/s41598-021-85057-0

55. Shahbuddin D, Othman A, Bukhary A, Khair A. Importance of High Crude Fibre Insect Frass for Effective Alleviation of Ammonium (NH_4^+) Toxicity and Optimal Growth of the Short-Term Vegetable, Amaranthus tricolor. Sains Malays. 2023;52(3):771-82. doi: 10.17576/jsm-2023-5203-07
56. Pacheco B, Aguirre-Becerra H, Feregrino-Perez AA, Garcia-Trejo JF. Effects of using thermocomposted frass from black soldier fly larvae as a germination substrate on the phytotoxicity, germination index, growth and antioxidant contents in kale (Brassica oleracea). Agronomy. 2024;14(7):1392. doi: 10.3390/agronomy14071392
57. Seifert CL, Moos M, Volf M. Different fates of metabolites and small variation in chemical composition characterise frass chemistry in a specialist caterpillar. Physiol Entomol. 2024;49(2):110-7. doi: 10.1111/phen.12429
58. Panche AN, Diwan AD, Chandra SR. Flavonoids: an overview. J Nutr Sci. 2016;5:47. doi: 10.1017/jns.2016.41
59. Jun JS. Investigating the Effect of Fermented Food on the Nutrient Content of Black Soldier Fly Larvae. In Proceedings of the 9th IRC Conference on Science, Engineering, and Technology (IRC-SET 2023). Singapore: Springer; 2023. pp. 470-8. doi: 10.1007/978-981-99-8369-8_44
60. Khoo HE, Azlan A, Tang ST, Lim SM. Anthocyanidins and anthocyanins: Colored pigments as food, pharmaceutical ingredients, and the potential health benefits. Food Nutr Res. 2017;61(1):1361779. doi: 10.1080/16546628.2017.1361779
61. Sen S, Chakraborty R. The role of antioxidants in human health. In: Oxidative stress: diagnostics, prevention, and therapy. Washington, DC (US): American Chemical Society; 2011. pp. 1-37. doi: 10.1021/bk-2011-1083.ch001
62. Rumbos CI, Karanastasi E, Athanassiou CG. Plant health promoting potential of insect frass: just a soil fertiliser or much more besides? J Insects Food Feed. 2025;11(7):1131-6. doi: 10.1163/23524588-110701ED
63. Biswas D, Sarkar R. Rise of marigold floriculture, a new stirring door walk through economic, social, and entertainment factors in Eastern India: a combined approach of multi-group structural equation modeling and cluster analyses. Qual Quant. 2023;57(1):137-72. doi: 10.1007/s11135-022-01347-3
64. Indore NS, Kale SJ, Akhoon AB, Singh RK, Singh H. Structural analysis of common existing greenhouses designs in different agro climatic zones of India. Int J Agric Eng. 2020;13(1):80-9. doi: 10.15740/HAS/IJAE/13.1/80-89
65. Bunpalwong M, Rukhiran M, Netinant P. Improving marigold agriculture with an IoT-driven greenhouse irrigation management control system. Bull Electr Eng Inform. 2023;12(6):3817-25. doi: 10.11591/eei.v12i6.6300
66. Chavez M, Uchanski M. Insect left-over substrate as plant fertiliser. J Insects Food Feed. 2021;7(5):683-94. doi: 10.3920/JIFF2020.0063

How to cite this article:
Chavez MY, Holley J, Craver JK, Velasco-Cruz C, Bousselot J. Increasing Rates of Black Soldier Fly (*Hermetia illucens*) Larval Frass Incorporation in African Marigold (*Tagetes erecta*) Production. J Sustain Res. 2026;8(1):e260041. https://doi.org/10.20900/jsr20260041.