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Applications of Black Solider Fly (*Hermetia illucens*) Larvae Frass on Sweetpotato Slip Production, Mineral Content and Benefit-Cost Analysis

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Abstract: Black soldier fly (*Hermetia illucens*) larvae (BSFL) production is increasing, which will leaves substantial amounts of leftover excrement, called 'frass' that may be a beneficial organic fertilizer. In this study, sweetpotato (SP) (*Ipomoea batatas*) cuttings ('slips'), were grown with BSFL frass as a one-time top dressing at either 333.7g/m^2 or 667.4g/m^2, respectively, or daily applications of either BSFL frass tea (225g in 3.78 L) or an inorganic fertilizer (control). The nitrogen-phosphorus-potassium of the BSFL frass and inorganic fertilizer was 6.2-1.4-1.7 and 10-30-20, respectively. After three weeks, no significant difference in length, number of nodes and stem diameter were found in the 667 g/m^2 frass treatment versus control, while these values were significantly lowest in the frass tea treatment. Slip manganese and copper were significantly lower and higher, respectively, in the control compared to the 333 and 667 g/m^2 frass treatments. Iron, copper, manganese, zinc and magnesium were significantly lower in slips from the tea treatment and was excluded from economical analysis due to minimal growth. Benefit-cost analysis showed the highest benefit-cost ratio was for the 333 and 667 g/m^2 frass treatments at 3.65 and 3.62, respectively, compared to the control at 3.48.

Keywords: black solider fly; frass; insect fertilizer; sweetpotato; slips; antioxidant

1. Introduction

Black soldier fly (*Hermetia illucens*) larvae (BSFL) are increasingly being investigated as sustainable ingredients in the diets of livestock, especially for poultry and fish [1,2] In addition to BSFL thriving on a wide range of waste streams, including manure, food waste, and agricultural by-products, they are also high in proteins and lipids [3]. Moreover, there are reportedly benefits to the BSFL inclusions in animal feeds such as reduction in pathogens in animal waste and improved overall health/growth [4,5]. Therefore, it is likely that BSFL production will increase in the coming years, which will also yield a greater amount of their by-product called 'frass'. Frass is a combination of insect manure that is rich in nitrogen, minerals and chitin, due to the continuous shedding of their exoskeletons, that has shown promise as an organic fertilizer.

Indeed, research has shown that BSFL frass can lead to similar plant growth compared to inorganic fertilizers [6,7] or even greater production [8,9]. For example, Beesigamukama et al. [9] found that BSFL frass improved maize production, which was attributed to higher mineral content and nitrogen equivalence values. There are also reports that the high chitin content in BSFL frass contributors to improvements in plant health and disease resistance [10]. Other benefits to using organic fertilizers in general includes a higher nutrient retention thus reducing excessive nutrient runoff as well as containing secondary nutrients and microbes that can improve soil quality in the long-term [11,12]. Interestingly, little research has included measuring the mineral content of plants after being grown in soil amended with BSFL frass. In one study, however, Agustiyana et al. [8] found that both phosphorus and potassium were approximately three and two-fold higher in pakchoi leaves after applying BSFL frass at 15%, respectively, compared to when a commercial synthetic fertilizer was used.

Sweetpotato (SP) (*Ipomoea batatas*) is the sixth most produced crop in the world [13] although their production has remained fairly steady from 97.7 to 91.8 million metric tons in 2001 and 2019, respectively [14]. Both the leaves and storage roots are consumed by humans as well as included in some livestock feeds [15–17]. A major obstacle in the farming of SP is the accumulation of viruses and mutations when farmers select SPs to use as 'seeds' from their previous year's harvest [18]. To combat this use, the use of virus-indexed planting material, known as 'slips', are produced with apical meristem culture and then are multiplied vegetatively to produce first generation material that can be sold to farmers. Indeed, the production and subsequent selling of SP slips is itself an industry, but shortages are still common [19]. Therefore, developing ways to optimize SP slip production would certainly benefit this industry.

Applying the right fertilizer is one of the ways to improve plant growth. Currently, slightly different nitrogen-phosphorus-potassium (NPK) values are used to culture SP slips. It is recommended that a balanced NPK of 10-10-10 or 12-12-12 should be applied [20] while others use 20-10-20 sometimes with applications of calcium and magnesium (Ca-Mg) [21]. However, there is limited information comparing the efficacy of inorganic versus organic fertilizer on SP slip production.

The aim of this study was to compare the growth, quality, mineral composition and total phenol/antioxidant activity of SP slips when receiving BSFL frass as a one time top dressing (at two different amounts) or repeated applications of BSFL frass tea or commercial inorganic fertilizer. An economic analysis was subsequently performed to assess the benefits and costs of producing SP slips using BSFL frass products versus a commercial inorganic fertilizer.

2. Materials and Methods

2.1. Source of Black Soldier Fly Larvae Frass

The BSFL frass was produced in the lab at University of Arkansas at Pine Bluff (UAPB) and the larvae were cultured according to Fischer and Romano [22]. The substrate used to feed the larvae were a combination of various grains, fruits, and vegetables. After three weeks of growing BSFL on this substrate, the resulting frass was collected and was oven dried (Despatch; LBB Series 2-12-3) at 100 °C for 48 h. The frass was then hammer milled into a fine powder and stored in plastic containers until use.

The composition of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), sodium (Na), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B) were measured at the Fayetteville Agricultural Diagnostic Laboratory at University of Arkansas with inductively coupled plasma (ICP) analysis. The mineral composition of the BSFL frass is shown in Table 1. The mineral composition of the BSFL frass tea is shown in Table 2.

Table 1. Mineral composition ('as is' basis) of black soldier fly (*Hermetia illucens*) larvae frass.

Macronutrients	%	Micronutrients	mg/kg
Phosphorus	1.44	Sodium	6200
Potassium	1.76	Manganese	76
Calcium	1.81	Zinc	372
Magnesium	0.38	Copper	44
Sulfur	0.56	Boron	24

Table 2. Nutrient composition (mg/mL) of the black soldier fly (*Hermetia illucens*) larvae frass tea.

Macronutrients	mg/mL	Micronutrients	mg/mL
Phosphorus	46.97	Manganese	0.001
Potassium	46.29	Zinc	0.11
Calcium	2.03	Copper	nd
Magnesium	2.43	Boron	nd

The bacterial composition from the BSFL frass was also determined by adding 0.25 g frass in 25 mL of sterile distilled water for 72 h. Next, these samples (200 µL) were spread onto Brain Heart infusion agar (BD Difco^{TM}), as non-selective agar, in quadruplicate. The plates were covered and kept under a sterile laminar flow cabinet. After 24 h of being incubated at room temperature (20 °C), all bacterial colony forming units were pooled in a sterile saline solution, 3 mL was centrifuged and the pellet resuspended in 200 µL of phosphate buffered saline. Bacterial DNA was extracted using 5x MagMAX Pathogen RNA/DNA Extraction Kit (Applied Biosystems TM Catalogue #: 4462359) and then isolated using an automated KingFisher Flex Purification system (ThermoFisher Scientific, Waltham, MA, USA). All steps to elution of highly pure DNA were performed according to the manufacturer's instruction and the DNA quantity was evaluated with Nano-Drop spectrophotometry (NanoDrop Technologies, Wilmington, DE, USA). After 72 h, the only cultivable bacteria were gram-negative that included *Acetobacter* sp., *Pseudomonas* sp., *P. graminis*, *P. syringae*, and *P. pumonensis*.

2.2. Source of SP Slips and Experimental Design

All virus indexed (virus-free tissue cultured) slips were provided by the UAPB Sweetpotato Foundation Seed Program. In a 29 m × 9.1 m high tunnel hoop house, Promix was used to fill 0.60 × 0.38 m (0.228 m^2) areas that were fitted with wooden frams to create a 15 cm deep planting area. Prior to planting, Promix was thoroughly mixed and saturated with water.

There were four treatments (in triplicate) that included a control (daily applications of a commercial inorganic fertilizer), 333.7g/m^2 of BSFL frass as a one time top dressing (hereafter referred to as '333 g/m^2 frass'), 667.4g/m^2 of BSFL frass as a one time top dressing (hereafter referred to as '667 g/m^2 frass'), and or daily applications of BSFL frass tea (225.0 g in 3.78 L), hereafter referred to as 'frass tea'. In each replicate, there were three rows of 26 SP cuttings and each row was spaced 6.3 cm apart. Each cutting measured approximately 10–13 cm in length and consisted of 4–5 nodes. Each day, the slips were watered with a hand sprinkler. The photoperiod was natural, and fans were automatically turned on when the temperatures exceeded 34 °C.

2.3. Sampling

After three weeks, all slips were measured for their lengths and stem diameters with a digital caliper, and then counted for the number of nodes, and finally weighed on a digital scale. A portion of the slips from each replicate were stored at −80 °C for later measurements of total phenol and antioxidant activity (Section 2.4). Another portion of the slips from each replicate were dried in a forced air oven at 60 °C for later determination of moisture content and mineral composition (Section 2.5).

2.4. Total Phenol, Antioxidant Capacity, and Chlorophyll Content

Leaves were freeze-dried and ground into a fine powder using a mortar and pestle. A sample was then measured for total phenol and antioxidant activity according to [23] that was optimized for SP leaves. Phenols and antioxidant activity were expressed as tannic acid equivalent (TAE; µg/g dry weight) and Trolox equivalent antioxidant capacity (TEAC; µg/g dry weight).

The chlorophyll content of the SP leaves was measured in triplicate according to the dimethyl formamide method as described in [24]. The leaves were weighed ~0.1g, and then

1mL of 80% ethanol was added, which was left overnight in the dark at 4 °C. After 24 h, the samples were centrifuged at 10,000 rpm for 10 min and then 200 µL of the supernatant was transferred into a 96-well microplate that was read at 664 nm and 647 nm. The absorbance for each wavelength were used to calculate the chlorophyll content [25,26].

$$[\text{Chlorophyll a}] = 12.7 * A_{664} - 2.79 * A_{647}$$

$$[\text{Chlorophyll b}] = 20.7 * A_{647} - 4.62 * A_{664}$$

$$[\text{Chlorophyll a + b}] = 17.90\ A_{647} + 8.08 * A_{664}$$

where A_{664} and A_{647} are the absorbance values from each wavelength.

Once the chlorophyll a, b, and a + b was calculated, those results were then divided by the weight of the sample to determine how much chlorophyll is present per gram.

2.5. Mineral Composition

The SP leaves were oven dried (60 °C for 24 h), digested at 115 °C for 30 min in 4 mL of trace-metal-grad HNO_3 (69%) and then 0.1mL of H_2O_2 (30%) was added with 40 mL of Milli-Q water. This solution was measured for iron (Fe), zinc (Zn), magnesium (Mg) and manganese (Mn) on a flame atomic absorption spectrophotometer (AAS) (iCE 3000 series, ThermoScientific, USA) with deuterium lamp background correction. Calibrations were made with single element standards (CPI International, Santa Rosa, CA, USA). The total phosphorus (P) content of the SP leaves was too low for AAS detection and therefore P was measured with the persulfate digestion method (HACH method 8190).

2.6. Economical and Statistical Analysis

The price of virus-free SP slips varies between $1.00–$1.50/slip and should have at least six nodes and "not be too stringy". To assess the economic feasibility and comparison among treatments an enterprise budget was conducted [27]. This included the total revenue, total costs, net returns, breakeven price (BEP), breakeven yield (BEY) and benefit-cost ratio (BCR). The price of the BSFL frass at $4.50/kg is based on typical market prices observed from various companies online in the United States.

Data from the SP production, mineral composition, total phenol/antioxidant activities were analyzed with a one-way ANOVA, and if significant differences were found ($p < 0.05$), a Duncan's post-hoc test was run to identify differences among treatments. Statistical analysis was performed using SPSS (ver. 16, Chicago, IL, USA).

3. Results

3.1. Slip Growth and Quality

Slip length was significantly shorter in the frass tea treatment compared to all others, while the control was significantly longer compared to 333 g/m^2 frass treatment as well as the frass tea treatment (Table 3). The number of nodes on each slip along with the nodes/length were not significantly different among the control, 333 g/m^2 or 667 g/m^2 frass treatments, but were significantly lower and higher, respectively, in the frass tea treatment. The stem diameter was significantly greater 667 g/m^2 frass treatment compared to the control or frass tea treatments (Table 3).

3.2. Mineral Composition

Among the macronutrients in the SP slip leaves, there were no significant differences detected ($p > 0.05$) with the exception of Mg being significantly lower in the frass tea treatment. Among the micronutrients, Fe, Cu and Mn levels were significantly different. Fe was significantly higher in the control than in the 333 g/m^2 frass and frass tea treatments while Cu was significantly highest in the control than all others. Mn was significantly higher in the 333 and 667 g/m^2 frass treatments compared to the control or frass tea treatments. The Ni levels were not significantly different among the treatments (Table 4).

Table 3. Mean (±SE) length (cm), number of nodes, stem diameter (mm) and number of nodes/length of the sweetpotato slips after three weeks of being grown with black soldier fly (*Hermetia illucens*) larvae frass products or inorganic fertilizer.

	Length	Nodes	Stem Diameter	Nodes/Length
Control	83.89 ± 2.22 [a]	17.47 ± 2.05 [a]	3.45 ± 0.09 [b]	0.21 ± 0.02 [b]
333 g/m² frass	62.61 ± 8.59 [b]	14.52 ± 1.31 [a]	3.53 ± 0.11 [ab]	0.23 ± 0.01 [b]
667 g/m² frass	78.60 ± 6.60 [ab]	16.76 ± 1.54 [a]	3.75 ± 0.02 [a]	0.21 ± 0.02 [b]
Frass tea	17.53 ± 0.29 [c]	6.19 ± 0.13 [b]	2.78 ± 0.10 [c]	0.35 ± 0.00 [a]

Different superscripted letters in the same column indicate significant differences ($p < 0.05$) among treatments.

Table 4. Mean (±SE) mineral composition of sweetpotato slips after three weeks of being grown with black soldier fly (*Hermetia illucens*) larvae frass products or inorganic fertilizer.

	Control	333 g/m² Frass	667 g/m² Frass	Frass Tea
	Macronutrients (mg/g)			
Potassium	52.58 ± 8.80 [a]	46.65 ± 3.73 [a]	57.96 ± 4.89 [a]	45.69 ± 5.29 [a]
Phosphorus	1.85 ± 0.27 [a]	1.53 ± 0.22 [a]	1.65 ± 0.31 [a]	0.97 ± 0.13 [a]
Calcium	4.51 ± 0.37 [a]	3.73 ± 0.09 [a]	4.02 ± 0.10 [a]	4.86 ± 0.35 [a]
Magnesium	3.85 ± 0.05 [a]	3.56 ± 0.21 [a]	3.71 ± 0.18 [a]	2.99 ± 0.18 [b]
	Micronutrients (mg/kg)			
Iron	103.23 ± 7.14 [a]	85.87 ± 5.82 [b]	97.17 ± 3.30 [ab]	33.05 ± 2.32 [c]
Copper	2.25 ± 0.20 [a]	0.72 ± 0.11 [bc]	0.99 ± 0.39 [b]	0.03 ± 0.02 [c]
Nickel	1.16 ± 0.56 [a]	1.42 ± 0.27 [a]	1.46 ± 0.08 [a]	1.15 ± 0.24 [a]
Manganese	17.05 ± 3.26 [b]	41.96 ± 7.09 [a]	50.43 ± 4.64 [a]	28.86 ± 2.97 [b]
Zinc	34.05 ± 3.29 [a]	31.60 ± 1.40 [a]	34.36 ± 1.85 [a]	13.40 ± 3.20 [b]

Superscripted letters within each row indicate significant differences ($p < 0.05$).

3.3. Total Phenol, Antioxidant Capacity, and Chlorophyll Content

There was no significant difference in either the total phenol or antioxidant capacity among the treatments (Figure 1a,b). The chlorophyll a, chlorophyll b and total chlorophyll content of the SP slip leaves were all significantly lower in the frass tea treatment compared to the other treatments, while there was no significant difference among the control, 333 or 667 g/m² frass treatments (Figure 2).

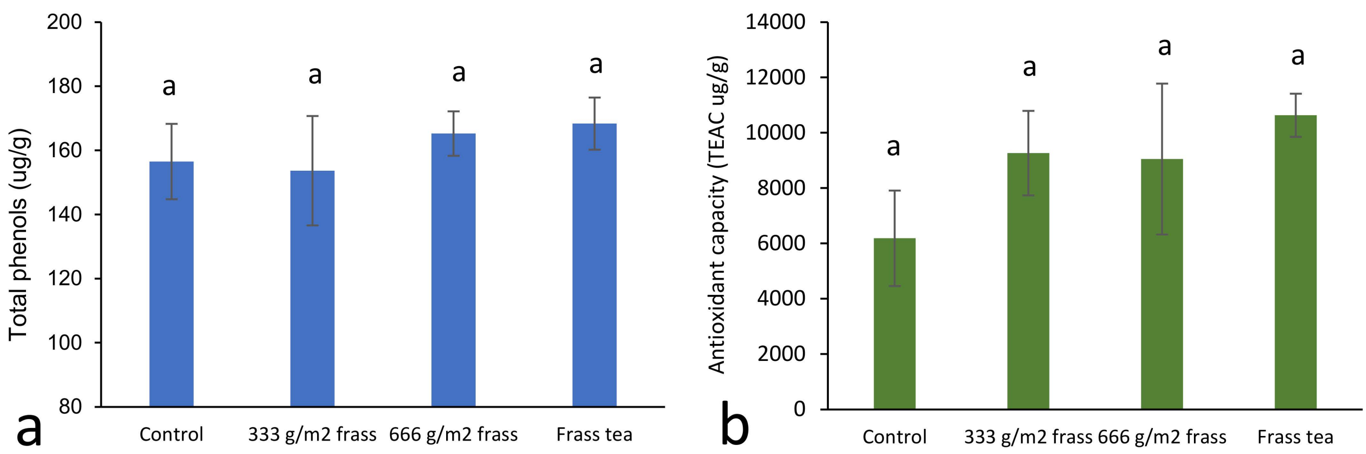

Figure 1. Mean (±SE) total phenol (**a**) and antioxidant capacity (**b**) in the leaves of sweetpotato slips three weeks of being grown with black soldier fly (*Hermetia illucens*) larvae frass products or inorganic fertilizer. No significant differences found ($p > 0.05$).

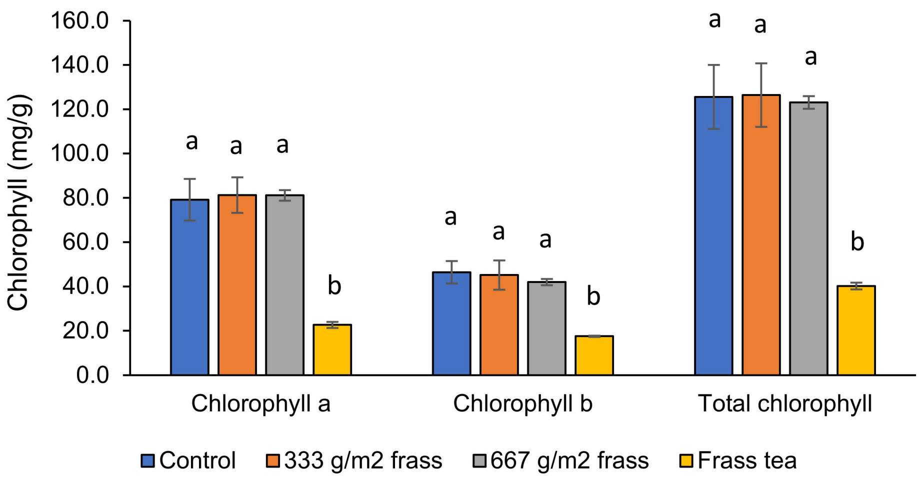

Figure 2. Mean (±SE) chlorophyll a, b and total chlorophyll (mg/g) content of sweetpotato slips three weeks of being grown with black soldier fly (*Hermetia illucens*) larvae frass products or inorganic fertilizer. Different letters above each bard indicate significant differences ($p < 0.05$).

3.4. Economical Analysis

The enterprise budget is based on one growing season with two harvests in a greenhouse (9.1 m × 27.4 m) that contains 40 tables (1092 slips/table). Thus, for two cuttings, a total of 87,360 slips (=2 × 40 × 1092 slips) can be harvested and sold in a year (growing season) from a greenhouse. If each slip is sold at $1.25, then a total return is likely to be $109,200. Assuming the number of slips and price is the same, the gross total return would also be the same for the control, 333 and 667 g/m^2 frass treatments. Each cutting was assumed to be one slip because they exceeded six nodes and would sell for the same price.

The total cost of production for SP slip production in a greenhouse in one year (season) will be $31,365 for the standard (control) method, $29,883 for 333 g/m^2 frass and $30,151 for 667 g/m^2 frass. Thus, the expected net return from SP slip cultivation in one season two harvests) will be $79,317 from 333 g/m^2 frass and $79,049 from 667 g/m^2 frass, compared to $77,835 for the standard (control) method. The expected return to land, family labor, and management from SP slip cultivation in one season will be $87,492 and $87,224 from 333 g/m^2 and 667 g/m^2 frass, respectively, compared to $86,910 for standard (control) method.

The estimated break-even price (BEP) for SP slips is $0.34/slip and $0.35/slip from 333 g/m^2 and 667 g/m^2 frass treatments, respectively, compared to $0.36/slip for the standard (control) method (Table 5). The estimated break-even yield (BEY) for SP slips is 23,906 and 24,121 for 333 g/m^2 and 667 g/m^2 frass, respectively, compared to 25,092 in the control. This indicates that to cover the costs of SP slip production at the given market price ($1.25/slips), it would be necessary to produce more in the control and the least in the 333 g/m^2 frass treatment to reach break-even.

The estimated benefit-cost ratio (BCR) for the 333 g/m^2 frass treatment is 3.65, which indicates that each dollar invested for SP slip production will provide $3.65 in return. The estimated BCR for the 667 g/m^2 frass is 3.62, while in the case of the standard (control) method, the estimated value of BCR was the lowest at 3.48 (Table 5).

The estimated additional profit from SP slips from using 333 g/m^2 frass instead of the standard method of using fertilizer to the tune of $1,482 (as net return) or $582 (as a return to land, family labor, and management) in a year (growing season). The additional profit will be $1214 (as net return) or $314 (as a return to land, family labor, and management) in a year (growing season) due to the shift in production method from standard method with fertilizer to the 667 g/m^2 frass treatment. Compared to the 667 g/m^2, using 333 g/m^2 frass will lead to $268 more profit per year (Table 5).

Table 5. Enterprise budget for sweetpotato slip production.

Items	Unit	Price	Control		333 g/m^2 Frass		667 g/m^2 Frass	
		($/Unit)	Quantity	Amount ($)	Quantity	Amount ($)	Quantity	Amount ($)
VARIABLE COSTS								
Slips (Tissue Culture Costs)		0.25	43,680	10,920	43,680	10,920	43,680	10,920
Labor	Person-Hours	15.00	605	9075	545	8175	545	8175
Promix (Soil)	Bales	43.50	120	5220	120	5220	120	5220
Fertilizer	Bags	35.00	10	350				
BSFL Frass	Kg	4.50			26.8	268	53.6	536
Irrigation water (120 × four months)	USD			2000		1600		1600
Electricity	USD			500		400		400
Total Variable Cost	USD			28,065		26,583		26,851
FIXED COSTS								
Greenhouse (Depreciation Cost per production cycle)	USD			3300		3300		3300
Total Fixed Cost	USD			3300		3300		3300
TOTAL COSTS	USD			31,365		29,883		30,151
RETURN								
Slip Production (in 2-hravest) of Slips			87,360		87,360		87,360	
Gross Return	USD	1.25	87,360	109,200	87,360	109,200	87,360	109,200
Net Return	USD			77,835		79,317		79,049
Returns	USD			86,910		87,492		87,224
Break-Even Yield	of Slips			25,092		23,906		24,121
Break-Even Price	USD/Slip			0.36		0.34		0.35
Benefit-Cost Ratio (BCR)				3.48		3.65		3.62

4. Discussion

The significantly lower growth of the SP slips in 333 g/m^2 frass and frass tea treatments compared to the control (inorganic fertilizer) could be due to less avialble N and other nutrients that are needed during the early rapid growth of the plants [9]. This seems to be especially applicable to the BSFL frass tea in which B, Fe, and Cu were at undetectable levels but were substantially above the detection limit in the actual frass (as a top dressing). This was reflected, to some degree, in the mineral composition of the SP slip leaves. In particular, the leaves from slips grown with the frass tea treatment had significantly lower Mg, Fe, Cu, Mn and Zn levels compared to the control and 667 g/m^2 frass treatment.

Both stem diameter and distance between nodes are key features in the assessment of SP slip quality. Farmers prefer slips that have a larger stem diameter with closer nodes because this often leads to greater production of storage roots in the field [19]. In this study, the 667 g/m^2 frass treatment produced slips with significantly larger stem diameters than the control, while the frass tea treatment led to the smallest. Moreover, the distance between nodes were the shortest in the frass tea treatment, while no significant difference was obtained between the top dressing frass treatments and the control. These parameters appear to indicate that the slip quality was not compromised by using BSFL frass as a nutrient source, and in fact, may actually improve their overall quality compared to the commercial fertilizer.

Fertilizer quality is often quickly gauged by NPK values because these macronutrients are essential for various processes in plants. In this study, the NPK values in the commercial fertilizer were substantially higher at 10-30-20 compared to the BSFL frass at 6.2-1.4-1.7. Nevertheless, the P and K values from the leaves were not significantly different from the control. This finding could be due to P and K being in more avialible forms, possibly by altering the bacterial composition of the soil towards P-solubllizing bacteria. For example, Agustinyana et al. [8] found that both P and K increased in the leaves of pakchoi with increasing BSFL frass applications, compared to an inorganic fertilizer, and suggested this was due to increased P-solublizing bacteria. Agustiyana et al. [8] did not clearly state whether or not the BSFL frass was heat treated prior to use, which would reduce or eliminate many bacteria. In this study, despite the BSFL frass being oven-dried at 100 °C for 48 h, there were several bacterial species identified. Considering this processing regime is sufficient to kill the identified bacteria, it may be possible that contamination occurred when the frass was being hammar milled and/or during storage. One notable bacteria included *Pseudomonas* sp., which is a P-solubilizing bacteria [28] and thus it is tempting to speculate this contributed to higher P content in the SP slips, especially considering BSFL frass had a substantially lower P content than the inorganic fertilizer.

It must be pointed out that *Pseudomonas syringae* was also isolated from the BSFL frass, which is one of the most common plant pathogens that infect the phyllosphere [29]. Not all strains are pathogenic [29] and the amount of *P. syringae* present in the frass was not enumerated. Klammsteiner et al. [6] found that potentially pathogenic coliforms were dominant in the BSFL frass (not heat treated), but when applied to the soil, it was concluded that BSFL frass would not negatively influence soil hygiene because autochthonous bacteria outcompeted others. These findings should encourage further studies on the bacterial composition of the soil after being amended with BSFL frass.

A striking observation between the one time top dressing frass treatments compared with the control and frass tea treatments were differences in the leaf color (Figure 3a–d). These differences could be attributed to 'chlorosis', which is a yellowing of the leaves due to a reduction in chlorophyll. Indeed, it was found that the chlorophyll content of the SP slips was signifcantly lower in the frass tea treatment, compared to the others. However, there was no difference in the control and one time top dressing treatments. Nevertheless, such differences in color may influence the willingness of farmers to purchase SP slips when grown with the inorganic fertilizer. There is limited information regarding the causes of chlorosis in SP slips; however, some of the factors that can influence chlorosis in other plant species includes deficiencies in Fe and Mn, which are exacerbated in low alkaline soils [30,31]. In this study, among the tested minerals in the SP slip leaves, Mg, Fe, Mn and Zn were all significantly lower in the frass tea treatments while only Mn was significantly lower in the control compared to the 333 and 667 g/m^2 frass treatments. It should be pointed out that this study was conducted over the summer where the air temperatures often exceeded 40 °C, despite the fans turning on, and high heat conditions may have also contributed to chlorosis [31].

The production of SP slips can be considered its own industry [19], and in fact, benefit cost analysis revealed that using the inorganic fertilizer or BSFL frass as a top dressing was highly profitable. However, using BSFL frass tea was excluded from economic analysis because farmers would unlikely purchase these slips based on their poor growth, limited number of nodes and stringy appearance with yellowish leaves. In fact, most failed to be considered as a 'slip' because the number of nodes were fewer than six. Interestingly, those cultured with BSFL frass was more profitable than the control. The higher profitability of using either 333 or 667 g/m^2 frass treatments was driven by a reduction in labor costs because these were a one time application whereas in the control, the inorganic fertilizer was daily prepared and applied. Willingness to buy should also not be discounted, with the SP slips produced with BSFL frass appeared greener and in the case of the 667 g/m^2 frass treatment, the stems were thicker (Figure 3).

Figure 3. Sweetpotato slips after 3 weeks of being grown with daily applications of an inorganic fertilizer (**a**), daily applications of black solider fly larvae (BSFL) frass tea (**b**), one time top dressing of BSFL frass at 333.7g/m^2 (**c**) or one time top dressing of BSFL frass at 667.4g/m^2 (**d**). The leaves in the BSFL frass treatments appeared greener with no chlorosis that may influence willingness to pay.

5. Conclusions

Overall, the use of BSFL frass as a one-time top dressing produced similar growth of SP slips compared with a commercially available inorganic fertilizer. Moreover, compared with the inorganic fertilizer treatment, benefit-cost analysis revealed that using BSFL frass as a one-time top dressing at 333.7g/m^2 or 667.4g/m^2 was more profitable due to a reduced need for labor. Considering organic fertilizers release nutrients more slowly than synthetic ones, it would be of economical interest to determine how many harvests could be obtained from the one top dressing application. It is not recommended, however, to use BSFL frass tea based on lower growth and poor appearance, which is likely due to lower levels of essential nutrients. The detection of a plant pathogen/probiotics in the BSFL frass might have implication for farming, which should be further explored including the implciations to the soil bacterial composition or ways for additional/more effective treatments to protect plant/soil health.

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