International Journal of Recycling of Organic Waste in Agriculture (2021)10: 185-202
Doi: 0.30486/IJROWA.2021.1899111.1071

ORIGINAL RESEARCH

Innovations in market crop waste compost production: Use of black soldier fly larvae and biochar

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Received: 22 May 2020 / Accepted: 22 February 2021 / Published online: 08 June 2021

Abstract

Purpose Compost production technology and use are known among Ghanaians farmers. However, the long composting period averaging three months has had adverse effect on adoption. The black soldier fly (*Hermetia illucens*) larvae (BSFL) feed voraciously and breaks down organic wastes fast. Addition of rice husk biochar (RHB) neutralises acidity and aerates the compost. Combined application of BSFL and RHB to feedstocks could therefore reduce composting period and improve compost quality.

Method Two studies were conducted with market crop waste (MCW) as feedstock. Firstly, feedstocks at two particle sizes (x < 5 mm and 5 mm < x >10 mm), with and without BSFL were evaluated to determine degradability, chemical content of the degraded residue and to select appropriate feedstock size ideal for composting. Secondly, the selected feedstocks size of between 5 mm and 10 mm were inoculated with or without BSFL and RHB of 0%, 5% 10% and 15% added. Composting trials were conducted in barrels inclined at 30^{o} to facilitate drainage. Physicochemical and biological parameters of feedstock were monitored until maturity.

Results Degradability of MCW by BSFL was feedstock specific rather than feedstock size. Inoculation of BSFL and biochar addition reduced composting period from 76 to 45 days. Biochar addition at 15% increased P availability to 1882 mg kg^{-1} but reduced total N to 10.5 g kg^{-1}. *E coli* levels decreased in the BSFL-biochar composts to acceptable limits.

Conclusion Composting MCW with BSFL and biochar reduced composting period and improved compost quality.

Keywords Feedstock, Organic waste, Co-composting, Inoculation, Degradation

Introduction

Organic waste forms more than 50% of the total waste generated in low and middle income countries (Couth and Trois 2010). In Ghana, organic waste generation is at the rate of 0.376, 0.249 and 0.172 kg/person/day, respectively, from Metropolitan, Municipal and District Assemblies. The high volumes generated constitutes about 61% of the total waste (Miezah et al. 2015). Pragmatic ways of efficiently managing organic waste have been non existent. However, organic waste remains the major contributor to environmental challenges in the urban areas of sub-Saharan Africa (Tumuhairwe et al. 2009).

Recycling of organic wastes to compost and the use of the amendment as nutrient sources by farmers can significantly reduce the cost and challenges associated with the importation of inorganic fertilizer into Ghana. Composting, while managing organic waste creates employment, closes the nutrient loop upon amendment of the product to soils and increases the organic matter levels of the fragile soils of sub-Saharan Africa. The production and use of organic fertiliser in sub-Saharan Africa will feed into the worlds' steady preference for organic agriculture in the stead of conventional agriculture. The organic fertilizer market was valued at $5.87

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billion in 2016 and has been projected to reach $11.16 billion by the year 2022 (AFO 2017).

Composting in Ghana is gaining recognition, especially among smallholder farmers. However, the long composting time and the low nutrient composition of the product are major challenges militating against adoption of the technology (Danso et al. 2006; Adamtey et al. 2009). Consequently, investment in compost plants in sub-Saharan Africa has been very low. The open windrow type of composting, which is the most common technology used in sub-Saharan Africa takes a minimum of three months to mature (Ofosu-Budu et al. 2008; Adamtey 2010). Conventional composting technologies like in-vessel and vermicomposting which can reduce the composting period significantly (Atiyeh et al. 2000; Manyapu et al. 2017) and improve the nutrient concentration in the final product also have their limitations. The in-vessel technology is associated with high installation cost and complexity in management. Temperatures are usually not high enough (< 35^{o}C) in vermicomposting to deactivate pathogens to acceptable levels, and hence the product often does not pass EPA standards.

In order to make composting attractive and woo investors into the industry, it has become necessary to develop a simple technology with low operational cost, which would produce a good quality product within a comparatively shorter period. An important variable in composting is the type of composting feedstock. The feedstock affects nutrient concentration and hence the quality of the final product. Market crop waste (MCW) being agricultural contains high levels of plant nutrients (Komakech et al. 2014; Akumah 2018; Singh et al. 2020) and could help produce good quality compost when harnessed (Aluko et al. 2020).

A major factor that prolongs the maturation of compost is the time needed to degrade the feedstock to a large enough surface area for subsequent decomposition by microorganisms. In addition, the low pH as a consequence of organic acids production during decomposition of organic matter lowers the activity of bacteria; the major microorganisms involved in composting (Sundberg et al. 2004). Any mechanism or technology that would increase the surface area of feedstock faster and increase pH during the decomposition process should go a long way in shortening compost maturity period.

The larvae of the Black soldier fly (BSF) (*Hermetia illucens*) have powerful mouthparts. They also have efficient enzymatic activity of the digestive system which enable them to feed on different types of organic substrates (Diener et al. 2009; Kim et al. 2011; Ewusie et al. 2018). The larvae are able to degrade large volumes of organic wastes of varying composition by up to 70% faster than other known species (Diener et al. 2011). This voracious attribute of the BSF larvae offers a promising opportunity of managing organic waste in a more sustainable way (Myers et al. 2014; Ewusie et al. 2018). The ability of BSF larvae to reduce the size and consequently increase the surface area of organic waste in a short time could be exploited to shorten composting time.

Biochar is an organic material produced from the pyrolysis of biomass in a zero to limited oxygen environment (Verheijen et al. 2010). Depending on the feedstock type and charring temperature, biochar may vary in pH from neutral to basic (Verheijen et al. 2010; Eduah et al. 2019). The basic pH and high concentration of basic cations in biochar (Sam et al. 2017; Frimpong Manso et al. 2019) may nullify the effect of released organic acids during the initial stages of composting, particularly when acid feedstock like fruit wastes are used. Biochar could also help minimise N loss by adsorbing NH_4^+, NO_3^- and NH_3 (Clough et al. 2013), and consequently improve the quality of compost. The pores in the biochar may also serve as sites for microbe habitation. The high available P content of biochar (Sam et al. 2017; Eduah et al. 2019) may also increase the available P content of the matured product. It is, therefore, expected that the use of BSFL in composting would hasten the breakdown of organic material and increase its surface area. Biochar will adsorb moisture when co-composted with MCW; thereby, aerating the system especially when MCW feedstock with high moisture contents are used. Additionally, co-composting with biochar is expected to nullify the effect of organic acids released leading to increased microbial (bacteria) activity to enhance early compost maturity. This study hypothesizes that (i) MCW streams will be suitable for BSFL degradation regardless of the feedstock size. (ii) The use of BSFL and biochar in co-composting MCW will enhance compost maturity and quality.

The objectives of this study were to determine the MCW streams and particle sizes that would be most suitable for degradation by BSFL for subsequent composting thereof and to determine the influence of biochar addition and/or BSFL inoculation on maturation and quality of MCW compost.

Materials and methods

Waste collection and treatment

Market crop waste is abundant during the rainy season (March to September) in southern Ghana (Akumah 2018) and served as feedstock for composting. The MCW collected from two major food markets in Accra were segregated into vegetable waste (VW) viz. cabbage, carrot and kontomire [KM], i.e., cocoyam leaves; fruit waste (FW), i.e., orange, watermelon [WM] and pineapple; fresh food waste (FFW), i.e., cassava, plantain and yam and other highly carbonaceous waste such as corn husk (CH) and plantain peduncle (PP). These feedstocks were air-dried to reduce their moisture contents, chopped using stainless steel machetes and knives and passed through a nylon sieve to obtain two different feedstock sizes of less than 5 mm and between 5 mm and 10 mm. The chopped feedstocks were placed in plastic baskets to allow for further sap drainage to reduce the moisture content in the vegetable and fruit wastes.

Experimental set up on BSFL degradation of two different feedstock sizes of the market waste streams

Eggs of the adult black soldier flies were collected from corrugated cardboard traps set on pig manure dump sites as outlined by Ewusie et al. (2019). The collected egg clutches were incubated to hatch into larvae in an earlier study (Ewusie et al. 2019). The larvae were then used for this study. Each of the two particle size fractions of the various MCW was mixed in various ratios indicated in Table 1 to formulate market crop waste mixtures on to which the BSF larvae (BSFL) were inoculated. The ratios were based on the quantity of the individual market feedstock assembled and the chemical characteristics of the waste (Table 2). Two kg of each of the mixtures were weighed on dry matter basis into 14.5 L plastic bins, and a total of two hundred and forty (240) hand counted five-day old BSFL were inoculated on to them. Equal quantities of the various mixtures without larvae inoculation served as the control. Each treatment was replicated three times.

The various mixtures with and without BSFL in the bins were covered with sewn muslin cloth shower caps held in place with elastic bands to prevent the entry of other insects and escape of the BSFL. The bins were then placed in a wire-meshed composting platform under ambient conditions in a Randomized Complete Block Design (RCBD). After 15 days of feeding (degradation), the larvae metamorphosed into pre-pupae and stopped feeding. The degraded market crop waste in each treatment was oven dried at 70^{o}C until a constant weight was attained. About 800 g of the oven dry degraded residues were passed through a 0.5 mm sieve and the < 0.5 mm fraction of each treatment recorded by weight.

Experimental set up for the determination of the influence of biochar and/or BSFL mediation on market crop waste compost maturity and quality

From the preceding experiment on BSFL degradation of MCW, the market crop waste streams suitable for BSFL degradation among the gamut of wastes collected from the two markets were identified as vegetable waste, fruit waste and fresh food waste. However, the moisture contents of the residue of the vegetable and fruit wastes after the 15-day degradation by the BSFL were still very high. Subsequently, the vegetable and fruit wastes were mixed with various proportions of rice husk biochar and fresh food waste (bulking agents) at varying concentrations of 0%, 5%, 10% and 15% as indicated in Table 3. Composting these mixtures was done in larger digesters fixed on wooden stands. The stands were inclined at 30° to facilitate drainage of any leachate from the composting mass. The digesters were fitted with outlet tubes at the lower ends to allow for the drainage of leachates. All openings of the digesters were covered with muslin cloth with apertures wide enough to allow for air circulation but small enough to prevent intrusion of other insects and escape of the BSFL.

Thirty (30) kilogrammes of the various feedstock mixtures indicated in Table 3 were weighed on a dry matter basis into the composting digesters.

Three thousand six hundred (3600) hand counted five-day old BSF larvae were inoculated onto each treatment. Similar treatments without larvae inoculation were set up to serve as control. All the treatments were replicated three times in a Randomized Complete Block Design (RCBD). After 15 days, the BSF larvae metamorphosed into pre-pupae and feeding ceased. The pre-pupae were then harvested from the mixtures. The mixtures were then turned twice a week until maturity. Steel probe thermometers of 15 cm length were used to monitor the temperature of the composting mass in the digesters until maturity. The matured compost was frac-

Table 1 Ratios of market crop waste used in the formulation of mixtures for BSFL composting*

Feedstock Combination	Ratio of Combination (2 kg dry matter weight)
CH: PP (CP)	0.3: 0.7
KM: cabbage: carrot (VW)	0.4: 0.3: 0.3
WM: orange: pineapple (FW)	0.5: 0.25: 0.25
Cassava: plantain (FFW)	0.7: 0.3
CH: PP: KM: cabbage: carrot (CP: VW)	0.15: 0.35: 0.2: 0.15:0.15
CH: PP: WM: orange: pineapple (CP: FW)	0.15: 0.35: 0.25: 0.125: 0.125
CH : PP : cassava : plantain (CP : FFW)	0.15: 0.35: 0.35: 0.15
KM: cabbage: carrot: WM: orange: pineapple (VW: FW)	0.2: 0.15: 0.15: 0.25: 0.125: 0.125
KM: cabbage: carrot: cassava: plantain (VW: FFW)	0.2: 0.15: 0.15: 0.35: 0.15
WM: orange: pineapple: cassava: plantain (FW: FFW)	0.25: 0.125: 0.125: 0.35: 0.15
CH: PP: KM: cabbage: carrot: WM: orange: pineapple: cassava: plantain (AF)	0.075: 0.175: 0.1: 0.075: 0.075: 0.125: 0.0625: 0.0625: 0.175: 0.075

*CH: corn husk; PP: plantain peduncle; WM: watermelon; KM: kontomire, VW: vegetable waste, FW: fruit waste, FFW: fresh food waste, CP: CH + PP, AF: combination of all treatments.

Table 2 Chemical characteristics of MCW feedstock and rice husk biochar used for composting

Treatment	pH	EC * 10^{-3}	C	N	C: N	T P	Av. P	K	Na	CEC
		(dS/m)	.... (g kg^{-1})......			.... (mg kg-1)..........		.... (g kg-1)......		(cmol kg^{-1})
Cassava	6.93 ±0.15	3.90 ±0.05	840.43 ±6.15	3.4 ±0.20	247.83 ±16.41	860.00 ±0.45	na	20.33 ±0.58	6.97 ±0.15	na
Orange	3.50 ±0.10	8.10 ±0.10	769.89 ±11.08	15.43 ±0.25	49.89 ±0.36	953.33 ±5.77	na	21.00 ±1.00	9.03 ±0.25	na
Plantain peduncle	9.93 ±0.42	12.88 ±0.02	845.80 ±15.17	5.27 ±0.3	160.93 ±8.97	1170.00 ±10.00	na	115.33 ±1.15	10.97 ±0.06	na
Kontomire	5.33 ±0.15	11.83 ±0.09	519.00 ±12.51	40.47 ±2.10	12.86 ±0.95	1456.67 ±11.55	na	75.33 ±1.53	12.00 ± 0.10	na
Carrot	8.57 ±0.31	7.34 ±0.08	666.47 ±26.99	12.93 ±0.61	51.67 ±4.43	1963.33 ±5.77	na	90.67 ±1.15	9.07 ± 0.40	na
Pineapple	5.03 ±0.25	7.83 ±0.08	748.57 ±14.29	21.47 ±0.74	34.89 ±0.81	966.67 ±5.77	na	31.33 ±1.53	8.03 ± 0.35	na
Corn husk	5.10 ±0.36	12.62 ±0.10	767.33 ±21.36	3.53 ±0.3	217.93 ±13.23	1050.00 ±10.00	na	18.33 ±1.15	11.03 ± 0.25	na
Watermelon	6.53 ±0.25	5.34 ±0.07	669.70 ±26.75	20.67 ±0.51	32.44 ±2.12	2050.00 ±7.42	na	97.33 ±1.15	8.07 ± 0.31	na
Plantain	7.00 ±0.20	4.18 ±0.06	744.47 ±9.47	8.77 ±0.60	85.17 ±5.60	1086.67 ±5.77	na	67.67 ±1.53	8.10 ± 0.10	na
Cabbage	5.20 ±0.10	12.83 ±0.15	656.38 ±11.55	36.00 ±1.73	18.25 ±0.55	1043.33 ±15.28	na	44.00 ±2.00	11.03 ± 0.85	na
Rice husk biochar	9.56 ±0.15	0.34 ±0.012	354.67 ±4.16	3.30 ±0.12	107.48 ±9.21	8236.67±196.04	2140.67±33.71	97.00 ±1.15	1.46 ±0.095	22.0± 0.91

Table 3 Feedstock-biochar ratio used in formulating mixtures for composting*

Treatment	Combinations
T1	0% Biochar + 45% VW (cabbage, carrot, "kontomre") + 40% FW (pineapple, water melon, orange) + 15% FFW (cassava, plantain)
T2	5% Biochar + 45% VM (cabbage, carrot, "kontomre") + 40% FW (pineapple, water melon, orange) + 10% FFW (cassava, plantain)
T3	10% Biochar + 45% VW (cabbage, carrot, "kontomre") + 40% FW (pineapple, water melon, orange) + 5% FFW (cassava, plantain)
T4	15% Biochar + 45% VW (cabbage, carrot, "kontomre") + 40% FW (pineapple, water melon, orange) + 0% FFW (cassava, plantain)

*VW-vegetable waste; FW-fruit waste; FFW-fresh food waste.

tionated using 0.5 mm, 2 mm and 4.75 mm sieves to determine the percentage size fractions. Moisture content was determined by oven drying the matured compost samples at 65^{o}C until constant weight was attained. Matured compost samples were taken for physico-chemical and microbiological analyses.

Germination Index (GI)

The germination test outlined by Zucconi (1981) was modified for use in this study. An extract of each of the compost was made by shaking a 1: 5 (weight/volume) compost to deionised water mixture for one hour and therefater filtered. Fifteen mililitres of the compost-water extract was used to moisten a filter paper lined petri dish. Fifty tomato seeds with almost 100% germination percentage were then placed in the lined petri dish. A similar set up using de-ionised water served as control. The two set ups were in triplicates. The petri dishes were closed and placed in the dark under ambient conditions for 72 hours. Germination percentage and root length of the germinated seeds were determined. The percentage seed germination, root elongation and germination index (GI) were calculated as follows:

$$Seed\ germination\ (\%) = \frac{No.of\ seeds\ germinated\ in\ compost\ extract}{No.of\ seeds\ germinated\ in\ control} \times 100 \quad [1]$$

$$Root\ elongation\ (\%) = \frac{Mean\ root\ length\ in\ compost\ extract}{Mean\ root\ length\ in\ control} \times 100 \quad [2]$$

$$Germination\ index\ (GI) = \frac{Seed\ germination(\%) \times Root\ elongation(\%)}{100} \quad [3]$$

Compost extracts that gave germination indices greater than 100 were adjudged matured and growth stimulating, while the ones that produced less than 100 germination indices were adjudged as not matured.

Chemical analyses

The matured compost samples were suspended in de-ionised water in a ratio of 1:10 (w/v), and the pH of the supernatant read using a digital Metrohm 691 pH meter. Electrical conductivity of the same suspension was read using an electrical conductivity meter. The total carbon and nitrogen contents of the samples were determined using a Carbon Nitrogen Sulphur Analyzer (Leco Trumac version 1.3). Total phosphorus, potassium and sodium were extracted by digesting 0.2 g of the samples with 25 mL mixture of concentrated HNO_3 and 60% $HClO_4$ in the ratio of 1:1.5. The concentrations of sodium and potassium in the digest were read on a flame photometer. Available phosphorus was extracted using the Olsen method and the P concentration in the extract and from the digest were read on a UV spectrophotometer after colour development by the Murphy and Riley (1962) method.

Microbial analyses

The methodology developed by Raj et al. (2014) was adapted and used in the microbial analyses of each of the matured compost. An equivalent of one gramme dry matter each of the matured compost types on fresh weight basis was weighed into 10 mL Falcon tubes and 9 mL of sterile Phosphate Buffer Salt solution was added. The mixture was allowed to stand for about 30 mins, after which the supernatant was pipetted into another 10 mL Falcon tubes and serially diluted. One mililitre aliquot of the serial diluent was used for membrane filtration. Determination of *Salmonella* species, *Enterococcus* species, total coliform and *E. coli* bacteria were then done using Bismuth Sulphite Agar, Slanetz, Bartley and HiCrome™ Coliform Agar media, respectively.

Statistical analysis

Data on pathogen counts were logarithmically transformed before statistical analysis. Shapiro-Wilk test was used to test for normality of data before subjecting it to one-way ANOVA test at a significance level of 5%. The differences among the mean values were determined using Tukey's test. All analyses were done using the GenStat 12 edition software.

Results and discussion

Effect of BSFL and feedstock size on the degradability of market crop waste

Microbial activities occur on the surface of organic materials and so when there is a decrease in particle size, microbial activity is hastened (Trautmann 2002). However, when the particles are too small, oxygen circulation is impeded, and the composting process is slowed down. The percentage of the < 0.5 mm residue from each of the two size fractions (< 5 mm and 5 mm < x < 10 mm) inoculated and un-inoculated with BSFL after 15 days of degradation are presented in Table 4. Generally, there was no significant difference ($P > 0.05$) in percent residual material from the two initial size fractions (< 5 mm and between 5 and 10 mm), irrespective of whether the crop waste mixtures were inoculated with BSFL or not. Thus, for ease of chopping, convenience and speed for feedstock processing, the bigger size fraction (between 5 and 10 mm) should be the preferred choice for composting.

The percentage of residue that passed through the 0.5 mm sieve from the BSFL mediated market crop waste was more than that from un-inoculated waste. The higher percentage of residue from the BSFL treatment could be attributed to the strong mouth parts and efficient digestive system of the larvae (Devic and Fahmi 2013). The percentage residue of the < 0.5 mm fraction was lowest in the CP, i.e., mixture of corn husk and plantain peduncle. The low degradability of the CP by the BSFL could be as a result of the low palatability of feedstock as evident in the very high C:N ratio of the corn husk (217.9) and plantain peduncle (160.9) and their relatively lower moisture contents as observed elsewhere by Cronjé (2004). In fact, without BSFL mediation, no particle from CP was less than 0.5 mm. After 15 days of larvae mediation, only 2% of the CP waste was less than 0.5 mm. However, without BSFL inoculation, approximately 23 to 25% of the VW from the initial feedstock sizes passed through the 0.5 mm sieve

This percentage increased to approximately 49% when the VW feedtock was inoculated with BSFL. On addition of CP to the VW (CP +VW), however, the < 0.5 mm fraction from the mixtures with or without BSFL inoculation was less than half the percentage when VW only was composted for 15 days. Conversely, degradability of CP improved from zero to between 10% and 11% when VW was added to the non-BSFL mediated mixture. Inoculation of CP + VW mixture with BSFL also improved degradability from 2% to between 24 and 25%.

Table 4 Effect of feedstock size (< 5mm and 5 mm <x< 10 mm) on the particle size of residue after 15 days of composting*

Treatment	L0		L1	
	(< 5 mm)	(5 mm < x< 10 mm)	(< 5 mm)	(5 mm < x< 10 mm)
	……………………………….%………………………………………………			
CP	0.00o	0.00o	2.00no	2.00no
VW	22.67fgh	24.67ef	48.67ab	49.33a
FW	16.00fghi	14.67ghijklm	39.33bcd	36.67cd
FFW	8.67klmno	8.33lmno	40.00abcd	36.67cd
CP + VW	10.00jkmn	11.33ijklmn	24.67ef	24.00fg
CP + FW	8.00lmno	7.33lmno	16.00fghijkl	14.00hijklm
CP + FFW	8.67klmno	6.67lmno	12.00ijklm	9.33jklmno
VW + FW	18.67fghij	18.00fghijk	41.33abcd	38.67cd
VW + FFW	12.67ijklm	11.33ijklmn	45.33abc	39.33bcd
FW + FFW	8.67klmno	8.67klmno	36.67cd	34.00de
AF	6.67lmno	6.00mno	23.33fgh	20.00fghi

***Means with same alphabets are not significantly different**

L0: no BSFL inoculation; L1: BSFL inoculation.

CP (corn husks + plantain peduncle); VW: vegetable waste; FW: fruit waste; FFW: fresh food waste; AF (CP + VW + FW + FFW).

Degradability of un-inoculated fruit waste after 15 days of composting was between approximately 15% and 16%. This increased more than two-fold to between 37% and 39% when BSFL was introduced into the mixture. On addition of CP, however, the un-inoculated mixture decreased in degradability by almost 8%, irrespective of initial size fraction. The inoculated FW + CP mixture also decreased in degradability by 22% to 23%. The fact that the larvae of BSF could not degrade the CP feedstock and there was a percentage decrease in quantity degraded when CP was combined with other feedstocks regardless of the feedstock size implies that BSFL degradation of organic material depends on feedstock type instead of feedstock size. This feedstock specificity of the insect is corroborated by the fact that the larvae were more efficient in degrading VW, FW and FFW.

When all the wastes were combined (AF), the degradability after 15 days was a paltry 6% to 7%, irrespective of initial size fraction. On inoculation with BSFL, degradability improved to between 20% and 23% as a result of the larvae's feeding habit. Black soldier fly larvae feed for between 21 to 24 days upon being hatched reducing volume of organic matter by 40% – 80% (Diener et al. 2011). The trial used 5-day old larvae for inoculation which meant that feeding lasted for between 16 to 19 days, all things being equal. The voracious feeding may have accounted for the higher increase in degradation observed in the BSFL treatments. After 21 to 24 days, the larvae turn into pupae and could be processed into feed meal for fish (Teye-Gaga 2017). The BSFL could thus play a major role in the transformation of tropical organic agriculture especially in sub-Saharan Africa by helping to close the nutrient loop.

The weight of residue after 15 days of composting which is an index of the extent of degradation of the various categories of market crop waste is presented in Table 5. The weight of residue from the various treatments, whether inoculated or not, did not show significant ($P > 0.05$) differences between the two initial size fractions. Size fractions above 0.5 mm from treatments without BSFL inoculation were significantly ($P < 0.05$) more than their counterparts with BSFL inoculation except in the CP treatment where similar weights were recorded. The highest degradation occurred in VW followed by FW. After 15 days, the BSFL had degraded 1.08 kg of VW, reducing the 2.00 kg waste by 54% to 0.92 kg in both feedstock size fractions. The VW and FW feedstocks are naturally very high in N and P (Table 2), the major nutrient needed by the larvae for growth. It is, therefore, not surprising that degradability of these two mixtures was faster than in the CP and FFW. The higher concentration of N which results in lower C: N ratio also makes the VW and FW more degradable compared to the more carbonaceous CP and FFW.

The CP feedstock of initial size fractions (< 5 mm and 5 mm < x < 10 mm) without BSFL inoculation had the lowest degradation of about 4% (Table 5). This percent degradation was not significantly ($P > 0.05$) different from the 10% degradation observed in the BSFL inoculated CP feedstock of similar size fractions. Degradation in the BSFL inoculated FW was about 47% while that in the inoculated FFW was between 32% and 34%. The respective 54%, 47% and 32-34% degradation observed in VW, FW and FFW were reduced to about 40%, 25% and 19.5% without BSFL inoculation. The higher degradability of VW and FW as opposed to the lower degradability of CP have implications for composition of mixtures to be composted. Should a composter inoculate BSFL onto the more degradable feedstock such as VW, FW or their mixtures in any ratios, less than half the initial weight would be left for further decomposition after 15 days.

Table 5 Feedstock size fraction and BSFL effect on the weight of residue after 15 days of composting as an index of degradation*

Treatment	L0		L1	
	(< 5 mm)	(5 mm < x< 10 mm)	(< 5 mm)	(5 mm < x< 10 mm)
	……kg……			
CP	1.91a	1.92a	1.8ab	1.83ab
VW	1.10opqr	1.20nopq	0.92u	0.92u
FW	1.35klm	1.33klm	1.08qrst	1.06rst
FFW	1.53efgh	1.56efg	1.33klm	1.36jkl
CP + VW	1.42hijk	1.44ghijk	1.22mnop	1.22mnop
CP + FW	1.60def	1.63cde	1.49fghij	1.50efghi
CP + FFW	1.71bcd	1.75bc	1.61def	1.61def
VW + FW	1.13nopqr	1.15nopqr	0.95tu	0.97stu
VW + FFW	1.35klm	1.37jkl	1.18nopqr	1.2nopq
FW + FFW	1.37jkl	1.38ijk	1.23mno	1.23mno
AF	1.24lmn	1.25lmn	1.07qrst	1.09pqrs

***Means with same alphabets are not significantly different**

L0: no BSFL inoculation; L1: BSFL inoculation.

CP (corn husks + plantain peduncle); VW: vegetable waste; FW: fruit waste; FFW: fresh food waste; AF (CP + VW + FW + FFW).

Blending the more nutritious feedstock with the highly carbonaceous feedstock like plantain peduncle, cassava waste or plantain waste would produce more material after 15 days for further decomposition. This would culminate in higher yield at maturity. This assertion is corroborated by the fact that when all the feedstocks were mixed to form AF, over 50% of the material was recovered after 15 days for further decomposition.

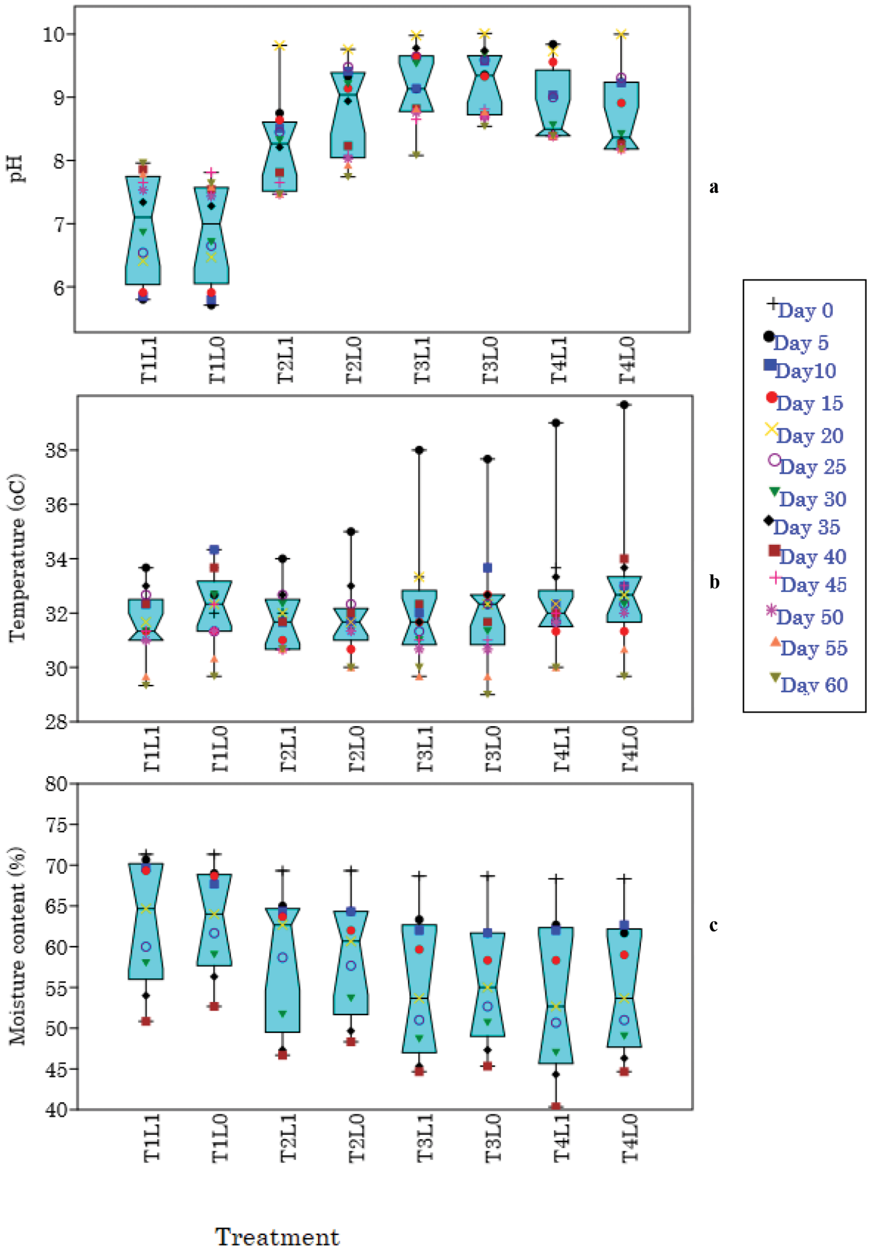

Fig 1. a-c Effect of biochar addition and BSFL inoculation on pH, temperature and moisture of feedstock during composting

Effect of biochar and BSFL on pH, temperature and moisture content during co-composting with MCW

The compost mixture without biochar (T1L0) had pH of 5.7 by day 5 of composting (Fig. 1a). Addition of 5% to 15% biochar showed increases in pH. The faster ammonification with its attendant release of hydroxyl ion (OH^-) coupled with the inherently high pH of the biochar (9.56) accounted for the increases in pH between 8.8 and 9.8 by day 5. Inoculation of BSFL onto the composting feedstock, however, showed no effect on pH. At compost maturity, the effect of the biochar manifested. The pH of BSFL and non BSFL mediated compost without biochar was 7.96 and 7.64, respectively. These pH values were not different from composts types with 5% biochar. However, increasing the concentration of biochar to 10% and 15% in the feedstock significantly increased the pH of matured compost to between 8 and 8.5.

The temperature at the onset of the composting process was 31°C for all treatments. This increased sharply to almost 40°C within the first five days especially in the 15% biochar amended non-BSFL (T4L0) and BSFL mediated (T4L1). Thereafter, the temperature decreased sharply by the tenth day, stabilising to that at the onset of composting by day 60 (Fig. 1b). The higher temperature increases in 15% biochar amended composts is obviously due to higher concentration of the material added. Biochar addition improves the homogeneity and structure of composting mixtures and this stimulates microbial activity leading to increased composting temperatures (Fischer and Glaser 2012). This resulted in shorter composting time.

Biochar has pores and can be hydrophilic. It may, therefore, have high adsorptive capacity for water (Sohi et al. 2010). The rice husk biochar used in this study might have adsorbed the excess moisture improving on oxygen intrusion. Consequently, there was improved microbial activity leading to temperature rise. This is further corroborated by the lowest temperature recorded in the non-biochar treated compost on day 5.

The rapid rise in temperature within the first five days of co-composting could be due to the activities of saprophytic microorganisms which drive temperature changes (Hassen et al. 2001). Thermophilic temperatures were not attained probably due to the high moisture content (60-70%) of the composting mixtures during the first five days of decomposition. Heat generated during composting should be insulated by the feedstock pile. However, the 60% -70% moisture of the composting feedstock offered poor insulation due to lower specific heat capacity compared to that of water (Haug 1993). The activities of black soldier fly larvae in the feedstock showed no particular effect on temperature just as was observed in the case of pH.

Moisture content at the beginning of composting was as high as 70% but with increased addition of biochar reduced to an acceptable level of 60-65% by day 10 (Fig. 1c). This could possibly be due to the hydrophilic nature of the biochar added which might have facilitated faster adsorption and evaporation of excess water (Sohi et al. 2010). However, inoculation of BSFL did not have any particular effect on moisture content.

Effect of biochar and BSFL on germination indices (GI) and compost maturity

The results of the GI of the various composts, as shown in Table 6, were above 100, which is an indication of compost maturity. Generally, BSFL mediated composts had higher GI (126 – 147) than their non-BSFL mediated counterparts (111 – 124). It is worthy of note that the compost prepared from feedstock without biochar and BSFL inoculation (T1L0) had the lowest GI of approximately 116. This compost type (T1L0) also took the longest period (76 days) to mature.

Biochar addition generally resulted in higher GI, especially in the BSFL mediated treatments.

The highest GI (147) and shortest days to maturity (45 days) were observed in the T4L1. Biochar with its alkaline pH must have neutralized the acidic effect of the organic acids produced culminating in higher GI. Delay in compost maturity could be from suppressed microbial activity as a result of organic acids produced during the initial stage of composting (Cherrington et al. 1991; Beck-Friis et al. 2003). The slightly acidic pH of 5.7 in the non-biochar composting mass and between 8.8 and 9.8 in the biochar amended counterpart by day 5 shows the positive effect of biochar in neutralizing acidity. The alkaline environment of the biochar amended feedstocks thus provided an enabling environment for increased microbial activity leading to early compost maturity. This is corroborated by the earlier studies of Sundberg (2005) and Jindo et al. (2012) who observed early compost maturity and reduction in phytotoxicity on co-composting organic feedstock with biochar.

It is worthy of note that for each feedstock treatment with 5% and 10% biochar, maturation period was 11 days shorter with BSFL inoculation than without. For the 15% biochar compost type inoculated with BSFL (T4L1), days to maturity was 5 days shorter than its corresponding counterpart without BSFL inoculation (T4L0). The 15% biochar and BSFL inoculation (T4L1) contributed positively to shortening of the maturity period by 31 days compared to the non-biochar and un-inoculated compost (T1L0). This has implications for investors and city authorities. The 45-day co-composting period would mean lower cost of production, all things being equal. This would mean more composting cycles in a year, leading to better management of organic waste and more availability of organic fertilizer.

Effect of biochar and BSFL on particle size of matured compost

Product particle size greater than 0.5 mm but less than 2 mm (0.5 mm < x < 2 mm) formed between 60% to 69% of the total mass of matured compost (Table 7). The proportion of this matured compost size fraction

Table 6 Effect of biochar addition and BSFL inoculation on days to compost maturity*

Treatment	Germination Indices (GI)	Days to Maturity
	Compost	
T1L0	115.81	76.33a
T2L0	124.42	64.33a
T3L0	111.32	64.00b
T4L0	124.45	50.33c
	BSFL Compost	
T1L1	126.12	76.00a
T2L1	134.66	53.00c
T3L1	132.68	53.00c
T4L1	147.34	45.00d

***Means with same alphabets are not significantly different**

T1L0: organic material + no BSFL, T1L1: Organic material + BSFL

T2L0: organic material + 5% biochar + no BSFL, T2L1: Organic material + 5% biochar + BSFL

T3L0: Organic material + 10 % biochar + no BSFL, T3L1: Organic material + 10% biochar + BSFL

T4L0: organic material + 15% biochar + no BSFL, T4L1: Organic material + 15% biochar + BSFL

Table 7 Percent particle size fraction of matured compost*

Treatment	< 0.5 mm	0.5 < x < 2 mm	2 mm < x < 4.75 mm
	………………………………	% ………………………………	
		Compost	
T1L0	14.58d	58.90e	26.52a
T2L0	19.00c	60.87d	20.13b
T3L0	19.50c	64.07c	16.43c
T4L0	20.50bc	66.23b	13.27d
		BSFL Compost	
T1L1	18.75c	61.33d	19.92b
T2L1	21.42b	63.75c	14.83cd
T3L1	24.08a	66.42b	9.52e
T4L1	25.33a	68.80a	5.87f

***For every column means with the same alphabets are not significantly different.**

T1L0: organic material + no BSFL T1L1: Organic material + BSFL

T2L0: organic material + 5% biochar + no BSFL T2L1: Organic material + 5% biochar + BSFL

T3L0: Organic material + 10 % biochar + no BSFL T3L1: Organic material + 10% biochar + BSFL

T4L0: organic material + 15% biochar + no BSFL T4L1: Organic material + 15% biochar + BSFL

seemed to increase with increasing biochar addition in both the BSFL mediated and non-BSFL mediated compost types.

The finer < 0.5 mm fraction was higher in the compost types with biochar than those without. An implication of the high proportion of matured compost within the fine earth fraction is that, on amendment, the materials will quickly homogenize with soil to increase soil organic matter levels. Consequently, there will be faster biochemical reactions to alter the physico-chemical and biological properties of the soil. The better aeration offered by the rice husk biochar as a result of lower moisture contents must have led to better microbial activity as evident in the first five days of sharp temperature rise. This resulted in a higher proportion of the finer particle sizes than their counterparts without biochar. This assertion is supported by the increasing finer particle sizes of compost with increasing percentage of biochar added.

For each of the compost types, there was significantly higher percentages of the < 0.5 mm and 0.5 mm < x < 2 mm size fractions in the BSFL mediated than the non-BSFL mediated. In the BSFL mediated with 10% and 15% biochar (T3L1 and T4L1) compost types, the fractions less than 2 mm were between 90% and 94%. The feeding style of BSFL certainly explains the higher finer particle size fractions of the BSFL mediated composts as was evident in the particle size as a result of the first trial.

Effect of BSFL inoculation and biochar on chemical characteristics of the matured compost

Compost suitable for crop production should have a pH range of 6.5 – 7.5 (Bary et al. 2002). Matured compost types without biochar, T1L0 and T1L1, and with 5% biochar addition, T2L0 and T2L1 had pHs within acceptable range for crop production due to their lower biochar concentration (Table 8). The pH values of 10% and 15% biochar-compost types were a little above 8 as a consequence of their relatively higher Ca contents (6–9 g kg^{-1}) (Table 8). The non-inoculated product and their inoculated counterparts had similar pH (Table 8) and thus it can be inferred that BSFL inoculation had no effect on the pH of the matured composts.

The electrical conductivity of all the compost types (< 0.007 dS m^{-1}) were far below the highest allowable level (< 4 dS m^{-1}) for farmland application (Bary et al. 2002). This implies that these materials could be amended to soils for many seasons without any adverse effect on soil structure. The very low EC could be due to the very low Na levels in the composts (Table 8).

Addition of 15% biochar and non-inclusion of the more carbonaceous FFW in the feedstock mixtures viz. T4L0 and T4L1 led to matured product with the lowest total C contents of 218 and 206 g kg^{-1}, respectively (Table 8). The decrease in total C concentration with addition of 15% biochar could be attributed to the relatively lower total C concentration in the rice husk biochar compared to the concentrations in the market waste feedstocks (Table 2). Most of the biochar carbon is in the recalcitrant pool compared to the non-biochar compost types which would have more labile carbon pools. This has implications in amending the product to soil. In instances where short duration crops and leafy vegetables, which require fast release of N, are cultivated, the preferred choice should be either T1L0 or T1L1. This is because of their higher labile carbon contents which would mineralize faster. In situations where farmers want to increase carbon stocks such as in the fragile savanna soils, then the T4L0 and T4L1 could be the compost types to consider. This is on account of their likely higher levels of recalcitrance which would confer on the soils some resistance to decomposition especially under the high temperature regimes of the savanna zones.

Increasing the concentration of biochar added to feedstock from 0% to 15% while decreasing the FFW content from 15% to nil tended to decrease the total N concentration in the matured composts (Table 8). Addition of 15% biochar to formulate T4L0 and T4L1 reduced the total N by more than 50% compared with their counterparts without biochar, i.e., T1L0 and T1L1. Inoculation of feedstock with BSFL, however, did not affect the total N concentration of the matured compost. This pattern of total N in the mature products could be due to the fact that the rice husk biochar used as a co-composting feedstock had a lower N content than its MCW feedstock due to the high charring temperature used to produce the former. Increasing the concentration of biochar with decreasing MCW content of the feedstock mixtures resulted in an overall decrease in N concentration due to the dilution effect of the biochar. The higher pH of the biochar added could have also contributed to N loss through ammonia volatilization which may, in part, account for the low total N content of the biochar-compost types, particularly the T4L0 and T4L1.

Black soldier fly larvae inoculation to organic feedstock was reported to significantly reduce N concentration in the final product (Newton et al. 2005; Ritika et al. 2015). In our study, however, there was no significant change in N concentration of the final product probably because of the advanced age of the BSFL used which meant shorter feeding period of 15 to 19 days.

Total P concentrations were statistically similar in all the matured compost types and ranged between 5410 and 7110 mg kg^{-1}. Available P concentrations, however, were higher in the 10% and 15% biochar compost types than their non-biochar compost counterparts. Introduction of BSFL did not alter the available P concentrations. The lowest available P concentrations were found in non-biochar composts (T1L0 and T1L1) where levels were between 1532 and 1618 mg kg^{-1}. The significantly higher available P concentration in the 10% and 15% biochar-compost over their non biochar counterparts (T1L0 and T1L1) could be as a result of the elevated levels of the nutrient in biochar as has been noted by Eduah et al. (2019).

Table 8 Effect of biochar and BSFL on chemical characteristics of matured compost*

Treatment	pH	EC	TC	TN	TP	Av. P	NH_4	NO_3	NH_4: NO_3	K	Mg	Ca	Na
	1:5 H_2O	dS m^{-1}	……….g kg^{-1}…………			……..............mg kg^{-1}…..............				..........................g kg^{-1}…...............................			
							Compost						
T1L0	7.64	0.0033d	306.6bc	28.07a	5.55a	1618de	4404d	2496a	1.77	73.87c	1.89a	1.06c	2.90cd
T2L0	7.74	0.0040cd	299.4bc	22.14c	6.10a	1702cd	4368d	451c	9.74	75.12bc	1.52a	2.17c	3.69bcd
T3L0	8.54	0.0051bc	318.1ab	22.13c	6.38a	1840bc	5660abc	462c	12.32	79.86b	1.83a	6.70b	4.15abc
T4L0	8.17	0.0066a	218.3d	10.97e	7.33a	2018a	4404d	821b	5.37	90.13a	2.25a	7.29b	5.22a
							BSFL Compost						
T1L1	7.96	0.0034d	288.2c	25.53ab	5.41a	1532e	5387bcd	2667a	2.02	73.03c	1.22a	1.04c	2.83d
T2L1	7.47	0.0044cd	331.4a	24.57bc	5.98a	1603de	6588a	574c	11.5	75.93bc	2.32a	2.21c	3.51bcd
T3L1	8.08	0.0042cd	329.5a	19.05d	6.05a	1706cd	6461ab	800b	8.12	77.69bc	2.34a	7.40b	4.23ab
T4L1	8.39	0.0063ab	205.8d	10.47e	7.11a	1882ab	4623cd	896b	5.2	89.37a	2.34a	9.22a	4.50ab

***Column means with the same alphabets are not significantly different.**

T1L0: organic material + no BSFL, T1L1: Organic material + BSFL

T2L0: organic material + 5% biochar + no BSFL, T2L1: Organic material + 5% biochar + BSFL

T3L0: Organic material + 10 % biochar + no BSFL, T3L1: Organic material + 10% biochar + BSFL

T4L0: organic material + 15% biochar + no BSFL , T4L1: Organic material + 15% biochar + BSFL

Composting is a dynamic process that involves the mineralization of organic N to NH_4^+ and the nitrification of NH_4^+ thereof to NO_3^-. The concentration of NH_4^+-N in the matured composts was still higher than NO_3^--N which shows that all composts types, albeit matured were not fully stable as noted by Tiquia et al. (1997). The initial 70% moisture content of the degrading compost might have inhibited nitrification. The biochar used for co-composting has a high CEC of 22 $cmol_c$ kg^{-1}. This implies that per kg of the amendment, the biochar has the ability of adsorbing 22 cmol of NH_4^+ and this may, in part, explain the slow oxidation of NH_4^+-N to NO_3^--N. The biochar seemed to have offered protection for the NH_4^+-N minimizing nitrification. This may be of great importance to agronomist and environmentalist as application of such compost types to soil will minimize nitrate leaching, especially in humid zones. The cationic available N was generally highest in the compost types with 10% biochar addition, i.e., T3L0 and T3L1 with values between 5660 and 6588 mg kg^{-1}. The NO_3-N in T1L1 and T1L0 was significantly higher than the rest of the compost types. Strikingly, compost without biochar had NO_3^- concentrations more than three times the levels in the matured products with biochar. It is also clear that the NH_4^+: NO_3^- in the compost were higher in the biochar compost than their non-biochar counterparts. In fact, the 5% and 10% biochar composts had ratios 4 times higher than their non-biochar counterparts. The higher NO_3^- N concentration in compost without biochar could be due to their longer composting time (76 days). The absence of biochar freed the NH_4^+-N culminating into higher nitrification. Though total N was lowest in the 15% biochar composts, the proportion of the total N available to crops at maturity was highest in those treatments. In fact, almost 50% of the total N in the T4L0 and T4L1 composts were in the available form as compared to between 25 and 32% for the non-biochar compost. It thus appears that the addition of biochar at 15% promoted more availability as a result of increased aeration and protection of the ammonium. The BSFL inoculation generally had no effect on levels of nitrate produced as concentrations were similar to those from the non BSFL mediated compost.

Biochar addition at 10% and 15% to MCW feedstock increased total K, Ca and Na concentration in the matured compost. This was as a result of the elevated levels of the nutrients in biochar as was reported by Eduah et al. (2019). These elevated levels may have also contributed to the higher pH of the 10% and 15% biochar type composts. Addition of biochar and BSFL showed no effect on the concentration of Mg in the matured product.

Effect of biochar and BSFL inoculation on the levels of faecal indicators and pathogenic bacteria in matured compost

The levels of faecal indicators and pathogenic bacteria present in the matured compost is presented in Table 9.

Table 9 Levels of faecal indicators and pathogenic bacteria in matured compost*

Treatment	*Salmonella spp.*	*E.coli*	Total coliform	*Enterococcus spp.*
	………	(log CFU/g)	………	
		Compost		
T1L0	0.00	4.09a	4.35a	0.00
T2L0	0.00	3.74b	4.14b	0.00
T3L0	0.00	3.68b	3.98c	0.00
T4L0	0.00	3.45c	3.94c	0.00
		BSFL Compost		
T1L1	0.00	2.91d	2.97d	0.00
T2L1	0.00	2.82de	2.94de	0.00
T3L1	0.00	2.71ef	2.81ef	0.00
T4L1	0.00	2.60f	2.69ef	0.00

***Column means with the same alphabets are not significantly different.**

T1L0: organic material + no BSFL T1L1: Organic material + BSFL
T2L0: organic material + 5% biochar + no BSFL T2L1: Organic material + 5% biochar + BSFL
T3L0: Organic material + 10 % biochar + no BSFL T3L1: Organic material + 10% biochar + BSFL
T4L0: organic material + 15% biochar + no BSFL T4L1: Organic material + 15% biochar + BSFL

Standard in compost class A: E. coli – 1000 MPN/g or log 3 CFU/g; Salmonella spp. – 3 MPN/4g (US EPA 2005, 2006)

Faecal coliform indicators and pathogenic bacteria levels in compost have been used as indices of quality of compost for crop production. Per the USEPA (2005, 2006), the level of *E. coli spp.*(3.45 – 4.09 log CFU/g) present in non BSFL mediated composts are too high for the amendment to be classified as a class A compost. These compost types should consequently have restricted application in crop production. They could be used in landscaping. The high moisture content of the mixtures at the onset and during composting which hindered the attainment of thermophilic temperatures may account for the high presence of *E coli* in the matured product. The *E. coli spp.* and total coliform in BSFL composts are below the USEPA (2005, 2006) standard and so fall under class A compost. These compost types can be used in crop production. In fact, BSFL inoculation to the feedstock without biochar reduced *E. coli* and total coliform loads in the matured compost by approximately 29% and 32%, respectively. Black soldier fly larvae have been known to reduce the level of pathogens such as *Salmonella enteritidis* (Erickson et al. 2004). The significant reduction in the pathogen level of the BSFL mediated compost could be due to the positive presence of the larvae. Increasing the concentration of biochar in the MCW feedstock to 10% and 15% tended to decrease the coliform counts in the composts. Addition of biochar increased the temperature over those without, and this could have accounted for the significant decrease in pathogen load in the 10% and 15% biochar compost types over their non-biochar counterparts.

Conclusion

Degradability of MCW streams by BSFL was feedstock specific rather than feedstock size. Biochar had a positive influence on compost maturity. Inoculating BSFL onto a mixture of 45% vegetable waste, 40% fruit waste and 15% biochar produced compost which matured in 45 days, 31 days shorter than composting the MCW without biochar. Inoculation of BSFL enhanced compost quality by increasing the surface area and reducing *E. coli* load in the matured composts.

The work has shown that co-composting MCW with BSFL and biochar is effective in shortening the composting time and reducing *E. coli* levels. This technology could be exploited by investors and municipal authorities in managing and valorising organic waste. The pupae of the black soldier fly could be used as feed in the poultry and aquaculture industry.

Acknowledgement The authors are grateful to the Swiss National Science Foundation (SNSF) for sponsoring this research. Other implementing organization such as Research Institute of Organic Agriculture (FiBL), Ghana Atomic Energy Commission, Biotechnology and Nuclear Agriculture Research Institute (BNARI) and University of Ghana are duly acknowledged.

Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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