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Development of Black Soldier Fly, *Hermetia illucens* (*Diptera*: *Stratiomyidae*) in Selected Organic Market Waste Fractions in Accra, Ghana

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Authors' contributions

This work was carried out in collaboration between all authors. Authors EAE, PKK, GOB and CS designed the study. Authors EAE, CTG and AA performed the statistical analysis. Authors EAE, PKK, GOB and CS wrote the protocol. Author EAE wrote the first draft of the manuscript. Authors EAE, CTG and AA managed the analysis of the study. Authors EAE, GOB, CS and EN managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To assess the effect of organic waste and their formulations on the development of the black soldier fly larvae.
Study Design: The experiment used one time feeding (lump feeding) of feedstocks obtained from

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organic market waste fractions and their combinations. The arrangement of composting containers followed a Randomized Complete Block Design (RCBD), replicated three times.

Place and Duration of Study: The study took 3 months and was conducted at the BSF laboratory of the Soil and Environmental Science Research Centre, Biotechnology and Nuclear Agriculture Research Institute of the Ghana Atomic Energy Commission in Accra, Ghana, West Africa.

Methodology: Two hundred and forty (240) hand counted 5-day old BSF larvae were inoculated onto 2 kg each of organic market waste fractions and their combinations in 60 L plastic containers covered with a mesh. Equal quantities of the above feedstock without larvae served as control. The arrangement of the containers followed a Randomized Complete Block Design (RCBD), replicated three times. Moisture content, larval growth parameters, temperature, relative humidity, prepupal development were recorded.

Results: Whiles moisture contents of most of the feedstock decreased gradually over the trial period, that of fruit waste only, fruit waste + corn husk and fruit waste + vegetable waste increased with time and was higher at the end of the trial than at the beginning. Composting temperature in all the feed stocks never reached the thermophilic stage and was between 29 – 38°C. The lowest temperature of 28.88°C was recorded in the mixture of vegetable waste and fruit waste whiles the highest, 37.55°C was recorded in the mixture of corn husk and uncooked food waste compost. Composting humidity ranged between 59 and 87% with significant differences being observed across treatments on days 0, 10, 15, 20 and 25. Larvae reared on a mixture of all the feedstock was significantly the heaviest (176.66 mg). Significant differences were observed in larval length and those fed with a mixture of fruit waste and uncooked food waste were the longest (17.66 mm). A highly significant number of eclosed adults, number of females and the number of egg clutches were observed among treatments.

Conclusions: Vegetable waste only, fruit waste only and a combination of vegetable waste + uncooked food waste; fruit waste +uncooked food waste; and a combination of all the wastes were the most preferred organic waste as they produced the optimum larval characteristics. The composting bins should be fitted with an outlet for leachates from the compost to drain out to avoid increase in compost moisture which will create anaerobic conditions that might delay compost maturity.

Keywords: Feedstock; municipal waste; larvae; egg clutch.

1. INTRODUCTION

Management of solid waste is a major challenge worldwide mainly due to growing global population, urbanization and economic growth, combined with varying production and consumption behavior [1,2,3]. Ghana, a low middle-Income country has for decades had difficulties in municipal solid waste management as a results of financial, infrastructural and technical inefficiencies [4,5]. The effect of poor environmental sanitation and solid waste in cities and communities in Ghana impend the realization of the Millennium Development Goal 7 (Ensuring Environmental Sustainability). Annually, Ghana generates about 3.0 million metric tonnes of solid waste [6,7) with a daily output of 13,000 metric tonnes of solid waste [8, 7]. The organics (vegetables, food, fruits, and greens) forms 44 – 65% of the total solid waste generated [9]. Only a small fraction of solid waste generated in Ghana is recycled mostly by the informal sector and a few private firms without any support from the authorities. This indicates an overwhelming dependence on landfilling, the least preferred waste management option on the waste management hierarchy [10]. Thus, there is little reuse of the organic fraction and hence, a large portion of the organic waste end up on landfill sites which reduces the life span of these facilities.

Removing the huge organic fraction from waste will thus reduce the volume of waste directed to dump sites, and will enhance the collection and storage of waste [11]. A universally accepted method of reducing organic waste volumes adopted by most countries is composting which may well involve microorganisms, worms, and also bio starters [12]. Composting presents a viable long-term option for the management of organic waste. There are clear environmental benefits from composting, including; the reduction of waste to landfill, reduction in greenhouse gases, conserve our resources and potential economic benefits [13]. Composting is a preferred and environmentally sound method whereby organic waste is reduced to organic fertilizer and soil conditioners through biological processes [14,15]. The high organic carbon content and biological activity of compost make it effective for applications such as erosion control and revegetation [16].

The black soldier fly, *Hermetia illucens* (L., 1758), (*Diptera*: *Stratiomyidae*) is a wasp-like non-pest species, 15-20 mm long [17] with worldwide distribution between about 45°N and 40°S [17,18]. The larvae of the black soldier fly have powerful mouthparts and efficient enzymatic activity of their digestive system and is thus able to feed on a gamut of organic substrates [19,20,21,22] obtained from both plants and animals thereby reducing and transforming these organic waste materials [23]. The larvae has been found to drastically reduce large quantities of varied organic matter by up to 70 % [24,25,26], faster and more efficient than other known species [26], while upcycling degrading organic waste to valuable animal protein, and thus offer promising opportunities for more sustainable ways of treating organic waste material. Use of larvae of *H. illucens* to treat organic wastes or livestock manure has been proposed as a promising and effective technology [27,28,25,29]. Black soldier fly larvae (BSFL) contain around 42% protein and 35% fat [30], based on dry matter, including favourable profiles of essential amino acids [31]. These properties make BSFL a suitable feed supplement candidate for various livestocks [32,33,20,34].

The moisture content of the feedstock intended for bioconversion by BSFL is important as it affects larval development [34,35]. Regan, et al. [36] and Murwira, et al. [37] reported that the optimum moisture content for compost is between 50 - 70% which is close to the optimum moisture range of diet of BSF larvae (60 - 90%) as reported by Myers, et al. [25]. Moisture content of feedstock below 40% and above 90% slows down larval feeding [35] and might even cause them to leave the feeding medium, thereby slowing down decomposition, hinders aeration, nutrients are leached out, and emission of odor as a results of anaerobic decomposition. Thus it is imperative that the moisture of any BSF larval feedstock should be monitored to ensure optimum degradation as well as larval growth and development.

Food handiness may affect larval and adult life history traits [38]. All earlier studies investigating the life history traits of *H. illucens* larvae and adults used artificial diets. Chemical Specialties Manufactures' Association (CSMA) [39] and Gainesville diets [40], which were developed for raising house flies, and a 15% protein layer ration [41], have been used to raise black soldier flies. May [42] also examined the development of the black soldier fly but failed to define the diet composition implemented. Before this study, the appropriate organic market waste fractions for decomposition by black soldier fly larvae was not known. Diener, et al. [23] used BSF larvae to bioconvert thoroughly mixed organic waste in Costa Rica, but they did not indicate the individual feedstocks and quantities used. That study nonetheless, showed that the technology can be used to manage organic waste in a Low and Middle-Income developing countries as well as deriving additional product (animal feed).

Temperature and humidity are important conditions for general living, growth and activities of insects. The ideal temperature range for survival, growth and reproduction of *Hermetia illucens* is between 27 and 36°C which guarantee 74 – 97% survival [43]. *H. illucens* larvae also consume waste in low temperature conditions but not very quickly because their behaviour is generally slower [44]. Additionally, temperature is one of the key indicators in composting. Changes in temperature are normally used as a measure of microbiological activity during composting as well as determining the stability of organic material [45]. Temperature in a compost heap characteristically follows a pattern of rapid increase to 49- 60°C within 24 - 72 hours of heap formation and is maintained for several weeks. This is the thermophilic stage of composting and involves the degradation of easily degradable compounds under aerobic conditions by organic refuse converters such as worms, microorganisms, houseflies and black soldier fly larvae [46,47,48,49,50]. The increased temperature kills pathogens, weed seeds, and phytotoxins. During this phase, oxygen must be supplied by either mixing, forced aeration, or turning the compost pile. As the active composting phase subsides, temperature gradually declines to around 38°C. Mesophilic organisms recolonize and the curing phase begins. However, these temperatures are far above the optimum temperature range for BSF development which had been predicted to be 27 – 36°C [43]. It would be thus be noteworthy to monitor temperature fluctuations during composting with *H. illucens* larvae.

The objective of this paper is to evaluate the suitability of the organic waste fractions in the Ghanaian markets for breeding of BSFL and the effect of these fractions on the growth rates of BSFL. The specific objectives were to assess the effect of organic market waste fraction on BSFL; (a) Co-composting temperature and humidity (b) Larval characteristics (c) Percent eclosion and (d) Adult egg clutch production. In particular, this study focuses on the identification of suitable waste fractions for breeding BSF larvae and for future production of high quality compost for use in the urban and peri-urban farming to improve soil fertility as well as harvesting of larvae as a protein component for animal and fish feed.

2. MATERIALS AND METHODS

2.1 Study Location

The study was conducted at the Ghana Atomic Energy Commission's Biotechnology and Nuclear Agriculture Research Institute farm in Accra, Ghana. The study site was located about 20 km north of Accra (05º40' N and 0º13' E), with an elevation of 76 m above sea level. Ghana is situated in West Africa, just above the Equator.

2.2 Black Soldier Fly Colony

The experiments were carried out at the Biotechnology and Nuclear Agriculture Research Institute, Ghana. The BSF larvae used were from a colony raised from wild collected eggs which has been breed over 10 generations at the BSF laboratory of the Soil and Environmental Science Research Centre, Biotechnology and Nuclear Agriculture Research Institute of the Ghana Atomic Energy Commission. Larvae were reared at a temperature range of 30-33°C, relative humidity of 58-71%, and 12:12 hour day: night period.

2.3 Market Waste Collection

Market wastes were procured from the Madina and Dome Markets which are in two different municipal districts in Accra, Ghana. The wastes were source separated and sorted into vegetable, fruit, uncooked food waste and material with high C/N ratio (Corn husk and plantain peduncle) (Fig. 2a). They were chopped (Fig. 2b) and sieved to pass through a 10mm mesh to increase the surface area and for easier consumption by the larvae. The feedstock were formulated based on the ratio in Table 1.

Fig. 1. Section of BSF hatchery

Table 1. Feedstock and ratio of combination for BSF composting treatment feedstock combination ratio of combination (kg)

Treatment	Feedstock combination	Ratio of combination (kg)
1	Materials with high C/N ratio (Corn husk +Plantain peduncle) (CH)	0.6: 1.4
2	Vegetable waste (Kontomire +Cabbage +Carrot) (VW)	0.8: 0.6: 0.6
3	Fruit waste (Watermelon+ Orange+ pineapple) (FW)	1: 0.5: 0.5
4	Uncooked food waste (Cassava +Plantain) (UCFW)	1.4: 0.6
5	Corn husk +Plantain peduncle + Kontomire +Cabbage +Carrot (CH+VW)	0.3:0.7:0.4: 0.3:0.3
6	Corn husk +Plantain peduncle + Watermelon +Orange +Pineapple (CH+FW)	0.3:+0.7:+0.5 +0.25 +0.25
7	Corn husk +Plantain peduncle + Cassava +plantain (CH+UCFW)	0.6 +1.4 +1.4 +0.6
8	Kontomire + Cabbage +Carrot + Watermelon +Orange +Pineapple (VW+FW)	0.4:0.3:0.3+0.5+0.25+0.25
9	Kontomire + Cabbage +Carrot + Cassava +plantain (VW+UCFW)	0.4: 0.3:0.3+ 0.7 +0.3
10	Watermelon +Orange +Pineapple +Cassava +plantain (FW+UCFW)	0.5 +0.25 +0.25+0.7 +0.3
11	Corn husk +Plantain peduncle +Kontomire +Cabbage +Carrot+ Watermelon +Oranges +Pineapple +Cassava + Plantain (CH+VW+FW+UCFW)	0.15 +0.35 + 0.2 +0.15 + 0.15+0.25 +0.125 +0.125 +0.35 + 0.15

Fig. 2. Organic market waste: (a) freshly collected waste (b) sorted waste being chopped to 10 mm particle size

2.4 Experimental Design

The experiments were conducted in a 60 L waste bins covered with a sewn muslin cloth shower caps with an elastic band (Fig. 3). Two hundred and forty (240) hand counted 5-day old BSF larvae were inoculated into 2kg of specific type of organic market waste fractions which has been chopped. The experiment used one time feeding (lump feeding) of feedstocks obtained from organic market waste fractions and their combinations as shown in Table 1. Equal quantities of the above feedstock without larvae served as control. The experiments were replicated 3 times in a mosquito-netted composting yard under ambient conditions. The

Fig. 3. Arrangement of composting bins in a mosquito-netted composting yard

arrangement of the containers followed a Randomized Complete Block Design (RCBD), replicated three times. Blocking was done to cater for any variability in the directions of both wind and sun in the mosquito-netted composting yard. The study was conducted from August to October, 2015.

2.5 Temperature, Relative Humidity and Moisture Content Measurements

Temperature and relative humidity at three different sections of each of the composting media were monitored daily at 10.00am using digital thermohydrographs and compost thermometer. Moisture content of the composting media were monitored every fifth day. A total of 10 g each of the eleven composting feedstocks without larvae were picked from different sections of each composing feedstock into already weighed aluminum cans and oven dried for 24 hours at 105^{o}C, [51] after which the samples were removed into a desiccator and the final weight determined. The weight of the aluminum containers were subtracted from both the initial weight and the final weight of the compost and moisture content determined using equation 1

% Moisture Content = (Wet weight – Dry Weight)/ Wet Weight x 100 (1)

2.6 Prepupae Collection and Setting

On the 16th day after larval inoculation when more than 50% of prepupae were observed in all of the composting feedstocks, they were hand-picked with the aid of forceps, counted and weighed after which they were kept in breathable plastic eclosion containers with crushed shredded papers as covering to induce pupation (Fig. 4a) and covered with a fine muslin cloth to prevent parasitoid entry and adult escape (Figure 4b). Thereafter prepupae were removed each day. All prepupae from same feedstock were pooled and 100 prepupae from each feedstock were kept in breathable eclosion containers with shredded papers and covered with muslin cloth were set aside for adult characteristics study.

2.7 Adult Maintenance

As soon as adults' began to eclose, the containers were placed in wooden adult cages measuring 80 x 80 x 80 cm (Fig. 5a) placed in a separate room roofed with transparent corrugated sheets to allow for indirect sunlight as sunlight was reported to encourage mating [52]. Temperature and relative humidity were monitored within adult cages using digital thermohydrographs. Fresh water was sprayed from a sprayer onto the muslin cloth covering of the adult cage to provide drinking water in suitable particle size and improve ambient humidity as the water evaporated. Adult mortality was checked 5 times a week and sexes of dead ones were counted and recorded.

2.8 Egg Clutch Collection

Moistened fresh larval diet was placed in transparent plastic containers (8 x 13.5 x 5 cm) part of whose covers have been cut and fitted with cut corrugated cardboards taped together with a masking tape. This setup served as egg harvesting device (Fig. 6b) to entice female flies to lay eggs and was placed in the adult cage (Fig. 5a) and partly covered with cardboard to

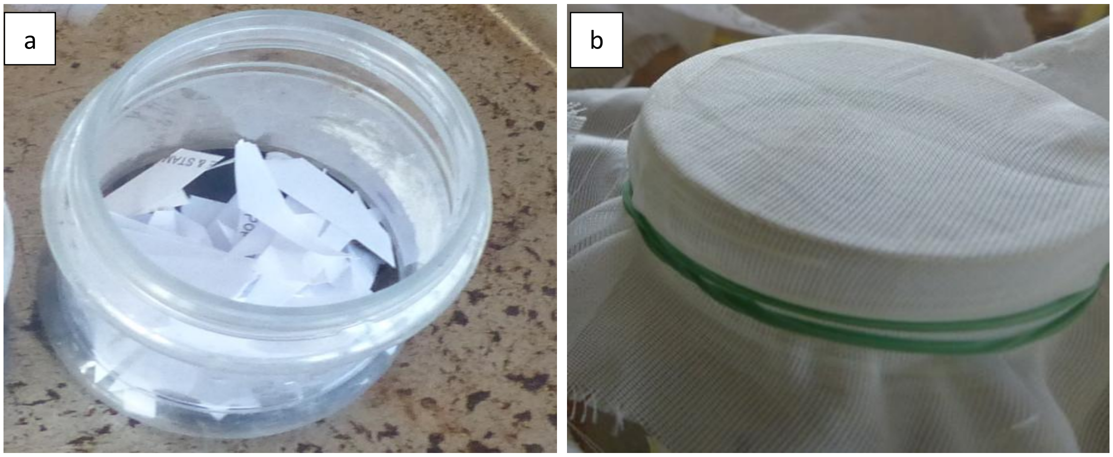

Fig. 4. a) Eclosion container with prepupae and shredded paper; b) Muslin cloth to prevent parasitoid entry and adult escape

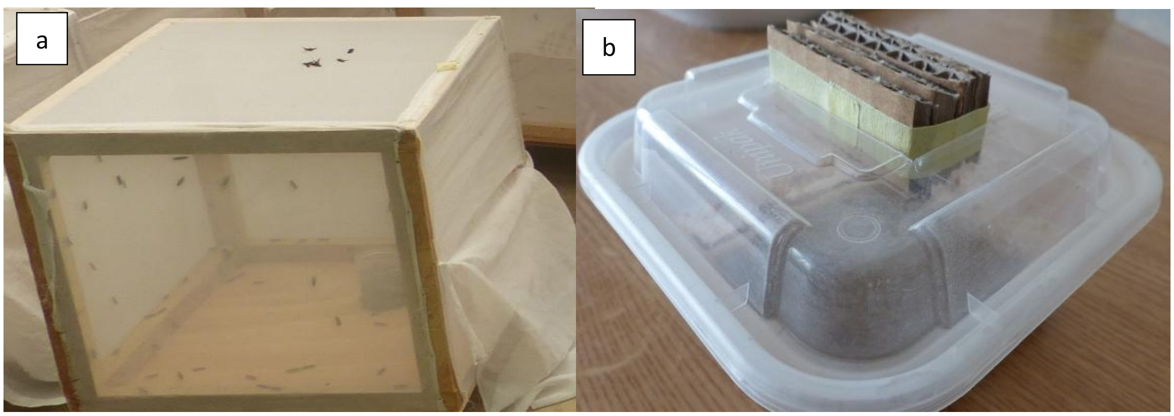

Fig. 6(a) BSF Adult cage; (b) Egg harvesting device

provide shade or hiding place. The egg harvesting device was checked five times a week and egg clutches sired were counted and recorded till all flies were dead in any particular adult cage. The number of egg clutches counted and recorded were divided by the total number of dead females in a cage to estimate female fecundity.

2.9 Data Analysis

All statistical analysis were done with both Microsoft Excel and GenStat software. Data were tested for homogeneity before being subjected to a single - factor ANOVA for statistical significance (α= 0.05) followed by Tukey-Kramer procedure to clarify which of the means were significantly different from each other.

3. RESULTS

3.1 Moisture Content

Moisture is necessary to support both feeding and metabolic processes of BSF larvae as well as microbes that might be in composting feedstock. Figure 7 shows the moisture content variations during the 20 days larval bioconversion process all of which were highly statistically significant (P < .001). The initial moisture content of the feedstock ranged between 61 – 91% which was within the range reported by Myers et al. [25]. Mostly the moisture content for the feedstocks decreased towards the end of the process except for fruit waste, corn husk+ fruit waste and vegetable waste + fruit waste. Whereas there was a gradual decrease in the initial moisture content of most of the feedstocks from day 5 till day 20, in the fruit waste only, and the mixtures of corn husk + fruit waste, vegetable waste + fruit waste, vegetable waste + uncooked food waste showed increases on day 5 and even at the end of the study. These feedstocks had still higher moisture contents than their initial.

3.2 Temperature and Relative Humidity

Table 2 shows the mean temperature patterns recorded in the selected market wastes undergoing decomposition by larvae of the black soldier fly. The highest mean temperature of 39.66±0.19 and 38.55±0.44 were recorded in vegetable waste +fruit waste and all the feedstocks combined respectively only at the beginning of the study, possibly due to increase in microbial activity [38]. Significant differences in temperature, (df =10, 22; F = 15.73, $P < .001$ and df =10, 22; F = 2.83; $P = .02$) were observed at 0 and 10 days respectively during the study. The lowest temperature during the bioconversion process was 28.33°C recorded in vegetable waste on day 20.

Table 3 also shows the relative humidity in the composting medium with time. Highly significant differences in humidity (df = 10, 22; F = 5.74; $P < .001$) were observed on the first day of composting only. It was again revealed that relative humidity was higher (71.44 – 81.88 %) at the end of the study in all feedstocks (Day 20) but these were suitable for the development of BSFL [53, 54].

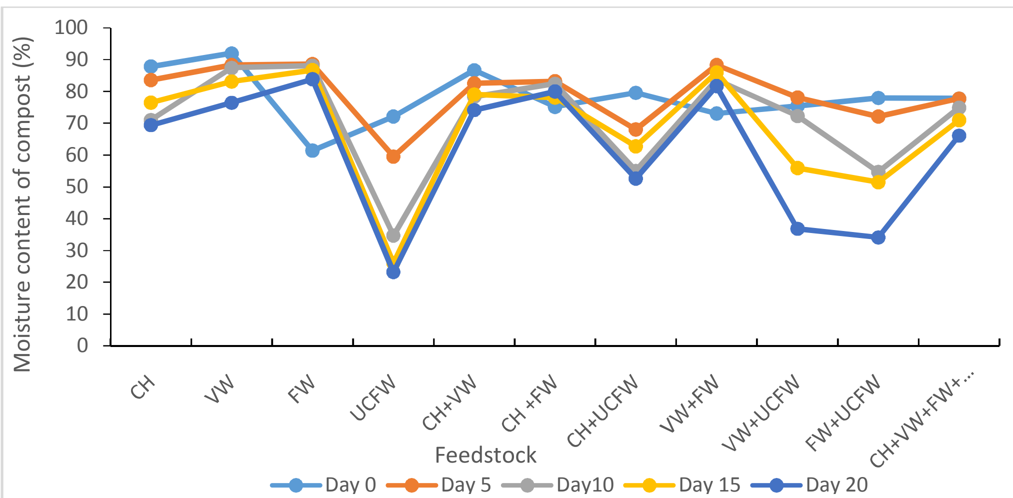

Fig. 7. Effect of age of compost on moisture content

Table 2. Mean (±SE) temperature of feedstock during bioconversion by BSFL

Treatment	**Temperature (°C)**				
	Age (Days)				
	0	**5**	**10**	**15**	**20**
CH	35.55±0.22de	30.88±1.22a	30.32±1.45abcd	30.44±0.62a	30.99±0.69a
VW	36.22±0.78cde	32.44±1.47a	32.55±1.28ab	30.11±1.11a	28.33±0.19a
FW	32.66±0.33f	32.22±1.36a	28.66±0.19d	30.66±0.88a	30.99±1.20a
UCFW	34.66±0.33e	30.99±0.38a	32.44±1.72abc	30.88±0.62a	30.11±0.67a
CH + VW	37.33±0.33bc	30.56±0.11a	29.66±0.66bcd	29.66±0.00a	32.66±0.33a
CH + FW	37.55±0.22bc	30.66±0.58a	30.88±0.72bcd	29.44±0.40a	29.77±1.23a
CH + UCFW	36.77±0.11cd	30.44±0.40a	29.99±0.33ab	30.55±0.39a	30.78±1.46a
VW + FW	39.66±0.19a	31.33±1.02a	32.88±0.58ab	28.88±0.22a	29.14±0.48a
VW + UCFW	35.22±0.80de	31.66±1.34a	33.33±0.50a	30.44±0.67a	29.44±0.86a
FW + UCFW	36.22±0.80de	32.78±1.74a	31.00±1.15abcd	29.11±0.48a	30.66±0.66a
CH+VW+FW +UCFW	38.55±0.44ab	33.44±1.42a	29.22±0.22cd	30.66±1.02a	31.77±0.73a

Within columns values with different superscripts are significantly different (P<0.05).

Table 3. Mean (±SE) Relative humidity of feedstock during bioconversion by BSFL

Treatment	Relative humidity (%)				
	Age (Days)				
	0	5	10	15	20
CH	64.66±0.19ab	64.55±2.68a	69.22±0.91a	72.10±0.78a	79.10±0.62a
VW	69.33±1.20b	64.55±2.74a	66.32±2.18a	73.99±1.86a	81.88±0.98a
FW	65.11±0.11ab	63.10±1.74a	67.22±1.84a	74.10±1.18a	77.33±0.76a
UCFW	64.33±2.00ab	61.88±3.72a	68.78±0.96a	71.99±0.84a	73.44±5.11a
CH + VW	60.78±0.22a	65.10±3.82a	68.99±3.24a	75.99±1.20a	72.55±2.45a
CH + FW	64.66±0.19ab	59.78±0.78a	66.55±2.99a	75.±1.20a	76.44±0.56a
CH + UCFW	67.44±0.62ab	65.44±5.16a	70.33±1.45a	73.33±2.08a	76.77±1.49a
VW + FW	62.66±1.50ab	60.77±.58a	69.10±2.07a	74.99±0.19a	77.66±1.20a
VW + UCFW	63.44±0.89ab	66.77±4.00a	71.77±0.48a	70.88±1.09a	76.44±2.72a
FW + UCFW	63.44±1.06ab	66.99±5.23a	71.77±0.48a	71.99±1.02a	71.44±2.92b
CH+VW+FW+UCFW	65.99±0.33ab	60.55±2.48a	65.66±2.52a	73.00±1.00a	76.66±2.87a

Within columns values with different superscripts are significantly different (P<0.05).

3.3 Larval Characteristics

The effect of the different organic market waste feedstock on larval weights and lengths are presented in Figs. 8 and 9. No significant differences in both larval weight and length were observed on the day of larval inoculation (Day 0). However, significant differences, $P < .001$ were seen from day 5 to 15 for both larval weight and length. All larvae attained their heaviest weight on day 10 after inoculation with the heaviest weight seen in the vegetable waste and uncooked food waste mixture (233.33 mg) but was not significantly different from that of vegetable waste, fruit waste and uncooked food waste mixture as well as that of all the feedstock combined (Vegetable waste + fruit waste + corn husk + uncooked food waste). However, at the end of larval feeding, the mean heaviest larvae were observed in the treatment composed of all the combination of feedstocks used (Vegetable waste + fruit waste + corn husk + uncooked food waste) (176.66±8.82 mg). Vegetable and fruit mixture feedstock produced the longest larvae on the 10th day (18.0mm), but on the last day of measurement, the longest larvae was seen with the fruit waste and uncooked food waste mixture (17.6 mm). The least heavy and shortest larvae were observed in the corn husk feedstock. Composting feedstock significantly influenced larval duration (df = 10, 22; F =812.34; $P < .001$ (Table 4), with the shortest revealed in uncooked food waste sample.

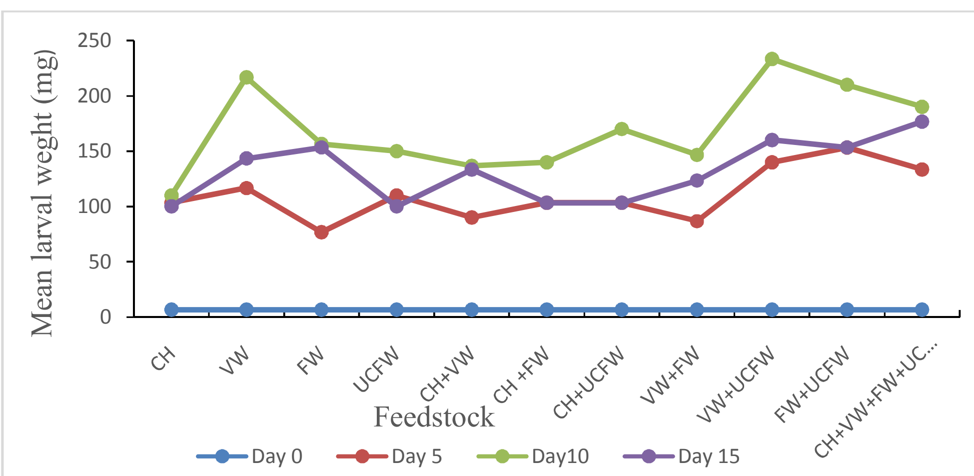

Fig. 8. Effect of feedstock on larval weight (mg)

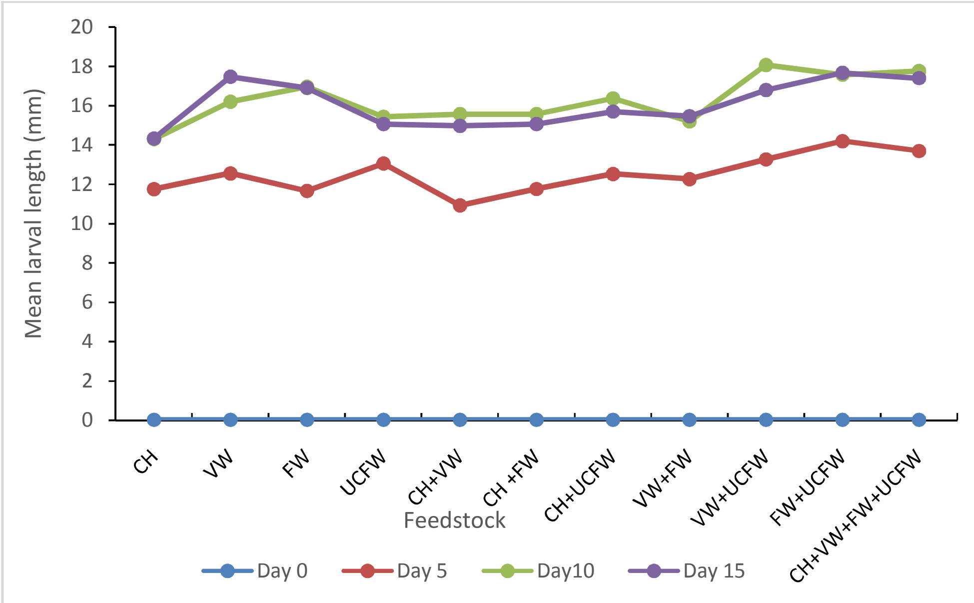

Fig. 9. Effect of feedstock on mean larval length

3.4 Prepupal, Pupal and adult characteristics

Mean prepupal weight across feedstocks was highly statistically significant (df =10, 22; F = 21.05; *P* < .001). For the eleven feedstock tested, the heaviest prepupae were obtained from the corn husk (20±0.28) (Table 4), whilst the least was those from a combination of corn husk + fruit waste (11.58±0.16). Highly statistically significant differences (df = 10, 22; F = 201.91; P < 0.001) were observed in percent adult eclosion. The highest adult eclosion was observed in both the uncooked food waste (65.74%) and the fruit waste + uncooked food waste feedstock (65.28%) but there was no significant difference between them (Table 4). A very low adult eclosion was seen in prepupae obtained from the vegetable waste + fruit waste mixture (18.75%). Highly significant differences (df = 10, 22; F = 26.26; P < 0.001) were observed in adult fecundity (Table 4). Even though, adult eclosion was least with prepupae obtained from the vegetable waste + fruit waste, its females were the most fecund producing a mean of 2.28±0.39 egg clutches per female whilst the least fecund females were those from the uncooked food waste that gave 0.41±0.02 egg clutch per female. This could be explained by the fact that fruits and vegetables are known to be rich in carbohydrates, fiber, high in potassium and an array of amino acids [54]. These nutrients are required for growth and particularly needed by the females to mature oocytes for egg production [55]. However, given the low eclosion rate of VW + FW diet, it may be necessary to reduce its percentage composition when formulating BSFL diet from organic waste fractions.

4. DISCUSSION

4.1 Moisture Content

Average percentage moisture of all feedstock in this study was 71 %. BSF larvae and even microorganisms can make use of organic molecules if they were dissolved in water. Regan et al., [36] and Murwira et al. [37] reported that the optimum moisture content for compost was between 50 - 70% which is close to the optimum moisture range of diet of BSF larvae (60 - 90%) as reported by Myers et al. [25]. Moisture content of feedstock below 40% and above 90% slows down larval feeding [35] and might even cause them to leave the feeding medium, thereby slowing down decomposition, hinders aeration, nutrients are leached out, and emission of odor as a results of anaerobic decomposition. There were gradual reduction of moisture contents of feedstocks every 5th day possibly due to assimilation of nutrients or proper mixing of food wastes by the larvae. However, in fruit waste only, the combination of fruit waste with corn husk or vegetable waste, there was a slight increase in moisture content as a results of the

Table 4. Effect of composting feedstock on mean (±SE) prepupal weight, larval duration, percent eclosion and egg clutch per female. N = 100

Feedstock	Prepupae (mg)	Larval duration (Days)	Eclosion (%)	No. of egg clutches per female
CH	20.00±0.28^{d}	18.33±1.20^{a}	28.47±0.40^{b}	0.50±0.00^{a}
VW	15.18±0.18^{bc}	17.00±0.58^{a}	46.52±0.40^{c}	0.71±0.04^{a}
FW	15.61±0.04^{c}	17.00±0.58^{a}	63.88±0.80^{ef}	0.96±0.20^{a}
UCFW	13.08±1.66^{abc}	18.33±1.20^{a}	43.75±1.20^{c}	0.41±0.02^{a}
CH + VW	11.83±0.18^{ab}	18.00±1.54^{a}	62.50±0.80^{ef}	0.46±0.01^{a}
CH + FW	11.58±0.04^{a}	17.00±0.58^{a}	51.38±1.60^{d}	0.62±0.02^{a}
CH + UCFW	16.63±0.03^{cd}	18.00±1.52^{a}	59.72±1.60^{e}	0.71±0.00^{a}
VW + FW	14.66±0.16^{abc}	19.00±1.52^{a}	18.75±1.20^{a}	2.28±0.39^{b}
VW + UCFW	15.62±0.04^{c}	18.00±1.15^{a}	46.52±0.40^{c}	0.48±0.03^{a}
FW + UCFW	16.12±0.04^{c}	17.33±0.88^{a}	65.28±0.80^{f}	1.89±0.02^{b}
CH + UCFW+VW + FW	16.15±0.02^{c}	17.00±0.58^{a}	65.74±1.66^{f}	0.99±0.01^{a}

Means followed by the same letter in a column are not significantly different (P<0.05)

fact that fruits and vegetables are soft textured with high moisture contents leading to rapid decay and retention of leachate in the composting bins. Thus further modifications has to be made in composting bins to ensure leachate drains into a collection bowl and possibly hasten compost maturity.

4.2 Temperature and relative humidity

Temperature and humidity are important conditions for general living, growth and activities of insects. The ideal temperature range for survival, growth and reproduction of *Hermetia illucens* is between 27 and 36°C which guarantee 74 – 97 % survival [43]. *H. illucens* larvae also consume waste in low temperature conditions but not very quickly because their behaviour is generally slower [44]. Furthermore, temperature is one of the key indicators in composting. Changes in temperature are normally used as a measure of microbiological activity during composting as well as determining the stability of organic material [45]. Temperature in a compost heap characteristically follows a pattern of rapid increase to 49- 60°C within 24 - 72 hours of heap formation and is maintained for several weeks. This is the thermophilic stage of composting and involves the degradation of easily degradable compounds under aerobic conditions by organic refuse converters such as worms, microorganisms, houseflies and black soldier fly larvae [46,47,48,49,50]. The increased temperature kills pathogens, weed seeds, and phytotoxins. During this phase, oxygen must be supplied by either mixing, forced aeration, or turning the compost pile. As the active composting phase subsides, temperature gradually declines to around 38°C. Mesophilic organisms recolonize and the curing phase begins. In our study, composting temperature never reached the thermophilic stage, with the highest being 39°C in all feedstocks combined, giving an indication of increased microbial action [56] only on the commencement of the study. This finding is significant, as the optimum temperature range for BSF development has been predicted to be 27 – 36°C and that temperatures above 36°C are lethal to the survival of *H. illucens* larvae [43]. Thus the temperature during larval decomposition not reaching the thermophilic stage was ideal for larval survival and development, giving an indication of the suitability of *H. illucens* larvae for composting. Although temperature has been associated with different stages of the composting process, this study found that compost temperature decreased without notable differentiation between stages, and this may be attributed to the feeding behaviour of *H. illucens* whereby they burrow and thus aerate the feeding medium [57, 58], reducing moisture and odour. This comes from their ability to modify the micro flora of the compost, reducing the harmful bacteria such as of E. coli 0157:H7 and Salmonella enteric [59] through production of bacteriostatic, bactericidal, and/or fungicidal compounds [59].

Just as temperature, relative humidity is an abiotic factor affecting insect development; however, unlike temperature, the effect relative humidity has on insect development is not predominantly studied [60]. The present study showed that organic market waste bioconversion by black soldier fly larvae resulted in higher relative humidity of the composting medium with time. However, these increasing temperatures were within the optimum for larval development.

4.3 Larval Characteristics

Feedstock had significant effect on larval weight and length but not on larval duration. This results indicate the ability of BSF larvae to develop and survive on a host of organic market waste fractions. Larval duration in all the feedstocks used were comparable to larvae fed on high protein and high lipid materials [61], but slightly longer than those fed on high protein standard layer feed [23,62]. It is probable that all the feedstocks could provide the necessary proteins and carbohydrates needed for BSF larval development [63,64]. There was a decrease in larval weight for all feedstocks during the study after day 10 and as the larvae reached the prepupal stage. This observation has been made by other researchers and has been attributed to; cessation of feeding, use of reserves for metamorphosis [65], and empting of larval digestive tract [66] in preparation for pupation.

Little is known about the mineral requirements of insects, but inferring from the known nutritive composition of insects [66], it is reasonable to surmise that sodium, potassium, calcium, magnesium; chloride and phosphate are essential minerals for the physiology of insects [67]. Nation, [67], showed that many phytophagous insects require quite large amounts of potassium and only trace amounts of sodium for their metabolism and growth. We found out that feedstock with over 60 % of organic carbon and pH near neutral enhanced BSF larval development. Trace amounts of other minerals may be necessary, but studies on mineral requirements for black soldier fly larval survival and development are lacking.

4.4 Prepupal, Pupal, and Adult Characteristics

Results presented showed that type of feedstock highly significantly affected prepupal traits such as prepupal weight (df 10, 22; $F = 21.05$; $P <$ 0001), pupal period (df 10, 22; $F = 194.84$; $P < .001$, egg clutch per female (df = 10, 22; $F = 26.26$; $P < .001$ and percent eclosion (df = 10, 22; $F = 166.59$; $P < .001$). All earlier studies investigating the life history traits of *H. illucens* larvae and adults used artificial diets. Chemical Specialties Manufactures' Association (CSMA) [39] and Gainesville diets [40], which were developed for raising house flies, and a 15% protein layer ration [43], have been used to raise black soldier flies. May [42] also examined the development of the black soldier fly but failed to define the diet composition implemented. Before this study, the appropriate market waste fractions for decomposition by black soldier fly larvae was not known. Diener et al., [23] used BSF larvae to bioconvert thoroughly mixed organic waste in Costa Rica, but they did not indicate the various feedstock and the quantities used. That study nonetheless, showed that the technology can be used to manage organic waste in a Low and Middle-Income developing countries as well as deriving additional product (animal feed). This study has confirmed the practicability of the BSF larvae surviving and developing on various municipal organic waste fractions. This study is expected to serve as an impetus to government, municipal and district assemblies as well as entrepreneurs to heavily invest in this technology for sustainable organic waste management in Ghana. Further research is however needed to monitor and improve the quality of the compost in order to reduce Ghana's dependency on inorganic fertilizer imports.

5. CONCLUSION

By reason of their generalist nature and high nutritional content, larvae of the black soldier fly is seen as a good candidate for addressing organic waste management, and serving as an alternate protein source for animal and fish feed production, two of the most important global issues of our time. This study is the first to investigate organic waste fractions of different moisture contents in the Ghanaian society that can serve as BSF larval diet and their impacts on life-history traits of the black soldier fly. Additionally, we summarize some past studies and offer a comparison to the results generated in this study (Tables 1– 4 and Figs. 1 - 3). These data provide valuable insights into the generalist nature of the black soldier fly larvae and its ability to utilize a variety of resources for larval development. A lot of the previous research work on the black soldier fly centered on the use of its larvae as a biological control agent of house flies and manure management agent in animal rearing facilities. Our study provides additional information on the life history of black soldier flies reared on market waste fractions. Thus, this work has shown that most of the organic fractions of the waste stream in the Ghanaian environment can support BSF larval growth and development. However, there is the need to exploit the mixing of these waste fractions in such a manner as to maximize the use of nutrients locked up in these waste streams. This information is necessary for developing its potential as an ecological engineer in managing municipal solid waste. However, because of the large differences between feedstocks, further research is needed to perfect and improve larval rearing for mass production of BSF larvae for animal and fish feed production.

In our experiments, *H. illucens* larvae consumed various decaying material. The largest larvae were after consuming vegetable waste only, vegetable waste + uncooked food waste, fruit waste +uncooked food waste and corn husk + uncooked food waste mixtures. These waste materials are suitable for consumption by *H. illucens* larvae.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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