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RESEARCH ARTICLE

SURVIVAL AND MORPHOMETRICS OF THE BLACK SOLDIER FLY, *Hermetia illucens* (DIPTERA: STRATIOMYIDAE) REARED ON COMMON MARKET FOOD WASTES IN NIGERIA

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ABSTRACT

Purpose: This study investigated the suitability of nine common market food wastes in Nigeria for rearing *Hermetia illucens*. Methods: Substrate suitability was determined through periodic assessment for survival, and measurement of body length, width and weight of *H. illucens* on each substrate in the laboratory. Results: Survival of *H. illucens* larvae and pre-pupae on maize flour, cowpea flour, over-ripe banana peels, amaranth leaves, watermelon peels, and bread was comparable to the control substrate (chicken feed). In contrast, survival of larvae to pre-pupae on cabbage and pineapple flesh was significantly lower than on the control. Generally, larvae and adults reared on chicken feed had significantly higher body size and weight compared to those on pineapple flesh or pineapple peels. Conclusion: Due to their inherently high moisture, low protein and low carbohydrate contents, pineapple flesh and pineapple peels are the least suitable substrates for *H. illucens* survival and growth in the study.

KEYWORDS

Municipal organic solid wastes, waste valorization, larval composting, larval biomass

1. INTRODUCTION

The world population is fast increasing and has been projected to be more than 9 billion by the year 2050 (United Nations, 2015). This projected population growth necessitates a 70 percent increase in food production to meet imminent increases in food demand and consumption (van Huis et al., 2013). As global food production and consumption increase due to rising populations and urbanization, it is expected that the amount of food wastes generated worldwide would also increase (Singh and Kumari, 2019; Kim et al., 2021). Food wastes refer to all components of food that are discarded during the production, distribution, sales, processing and consumption of food (Kim et al., 2021; Liu et al., 2016). Food wastes may therefore include kitchen, restaurant or market wastes generated from foods like cereals, pulses, vegetables, fruits, livestock meat, animal offals, and other plant and animal based foods (Kim et al., 2021, Kiran et al., 2014). Already, up to 1.3 billion tonnes of food from households and communities is wasted annually (FAO, 2011) with wastes from fruits, vegetables and cereals including rice accounting for about 7%, 20% and 30%, respectively of food wastes produced globally (Kiran et al., 2014). Furthermore, food wastes form between 25 – 45 percent of the more than two billion tons of municipal solid wastes generated globally (Nichols and Smith, 2019; Eggleston et al., 2019; Brás et al., 2020). Regrettably, only about 16% of all municipal solid wastes produced in the world are recycled annually (Kim et al., 2021, Brás et al., 2020; Eggleston et al., 2019). A large proportion of municipal organic solid wastes (MOSW) are dumped in landfills, and inappropriately on roadsides or in water channels. Annually, decomposing MOSW in landfills contribute to the increase in global emissions of methane and other greenhouse gases that are implicated in global warming and climate change (Sánchez et al., 2015; Samayoa et al., 2016; Couth and Trois, 2009). Thus in addition to potentially contributing to food insecurity, global increase in food wastes can have deleterious effects on human health and environment (Nichols and Smith, 2019), especially in the poorer regions of the world. The foregoing thus highlights the importance of efficient and sustainable waste management strategies.

The treatment or composting of MOSW with larvae of the ubiquitous black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae) has in recent times gained popularity for its cost-effectiveness, and sustainability (Lalander et al., 2019; Singh and Kumari, 2019; Liu et al., 2019; Kim et al., 2021). The Black Soldier Fly (BSF) has five distinct life stages viz egg, larva, pre-pupa larva, pupa, and adult (Da Silva and Hesselberg, 2019). Female flies lay about 400 to 800 eggs in dry sheltered cavities close to decomposing organic materials or waste streams (Dortmans et al., 2017). Eggs hatch into neonate larvae within an average of four days, after which they feed voraciously on available organic wastes, and develop through five larval instars between 14 – 16 days under optimal conditions (Dortmans et al., 2017). At maturity, the final larva which is about 25 mm long and 5 mm wide becomes a pre-pupa that is dark brown to charcoal grey in color. The pre-pupa empties its digestive tract and does not feed. Instead, it replaces its mouthpart with a hook-like structure with which it drags itself out of the food substrate to a dry and safe pupation site (Dortmans et al., 2017; Da Silva and Hesselberg, 2019). Pupation in BSF takes an average of eight days with a range of between two to three weeks, depending on prevailing conditions. At the end of pupation, the adult flies emerge from the pupal case, and repeats the mating and egg-laying cycle for 5 to 8 days after which they die (Da Silva and Hesselberg, 2019). Adult BSF do not feed on anything except water. Instead they rely on fat stored during the larval stage for their nutrition. In addition, the flies do not harm humans, crops or animals, and do not vector any pathogens (Diener et al., 2011).

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The Black Solider Fly Larvae (BSFL) is able to feed and grow on a wide array of waste streams including food wastes, livestock manure and human excreta (Diener et al., 2011; Zhou et al., 2013; Lalander et al., 2013; Oonincx et al., 2015). The BSFL is favoured above other fly larvae for waste valorization because of its excellent ability to convert organic wastes into quality larva-meal with 30-40 % protein and 28-35 % oil contents, and organic compost (Zhou et al., 2013; Cickova et al., 2015). In view of rising prices of livestock feed ingredients, especially fish meal and oils, BSFL provide a sustainable alternative source of cheap and high-quality animal-protein (Spring, 2013; Lalander et al, 2019). In addition, fats obtained from defatted BSFL can also serve as excellent alternatives to edible oil crops for the production of high-quality biodiesel (Schiavone et al., 2017; Ewald et al., 2020). Despite its potentials to grow on a variety of waste streams, studies have shown that biomass quality, nutritional composition and development duration of BSFL is affected by the types and composition of rearing substrates amongst other factors (Spranghers et al., 2016; Cammack and Tomberlin, 2017). For example BSFL reared on a protein or fibre rich-substrate developed at a much slower rate than those reared on a balanced diet of processed cereal leftovers (Tschirner and Simon, 2015). Also, BSFL survival on digested sludge, restaurant wastes, fruits-vegetable mix, and poultry feed was 39%, 87%, 90%, and 93%, respectively.

In Nigeria, the actual inclusion of BSFL as a protein source component in livestock and aquaculture feed is just gaining prominence amongst farmers and feed millers (Omoloye et al., unpublished). Nevertheless, knowledge of its nutritional benefits in livestock and fish feed is fast increasing. In a recent baseline study conducted in Nigeria, about 77% of fish farmers and 94% of poultry farmers were willing to include BSFL as a feed component (Omoloye et al., unpublished). On the other hand, there is paucity of information on the application of BSFL-composting as a waste management strategy in Nigeria. To enhance the adoption of BSFL as an alternative source of protein in animal feed and a cost-effective waste valorization technology in Nigeria, increased low-cost production of BSFL must be achieved under artificial rearing conditions. This can be done by identifying cheap, ubiquitous and easily sourced MOSW in Nigeria with excellent potentials for rearing high-quality BSFL. However, studies on the suitability of common organic waste streams in Nigeria for BSFL rearing are scanty. Since the composition and quality of food wastes differ from country to country (Kim et al., 2021, Kiran et al., 2014), and even between rural and urban regions due to differences in consumption patterns (Boateng et al., 2016), we investigated the suitability of common food wastes generated in urban markets in Nigeria. Specifically, we studied the survival and morphometrics of Black Soldier Fly, *Hermetia illucens* L. reared on fruit-, vegetable-, and grain- wastes commonly generated in Nigerian food markets.

2. MATERIALS AND METHODS

2.1 *H. Illucens*

About three (3) days old *H. illucens* eggs were obtained from a local BSF farmer in Ibadan, Nigeria. The eggs were taken to the laboratory in the Department of Crop Protection, University of Ilorin, Ilorin, Nigeria were they were maintained at ambient conditions (29.4±0.9°C, 74.0±3.8 % R.H and 12-hour photoperiod) until hatching. Eggs hatched into neonate BSFL a day after receipt and were immediately transferred into chicken feed (Hybrid Feeds Super Starter for <2 weeks old broilers with ~ 70 – 80 % moisture content) on which they were reared for seven days until the start of experiments.

2.2 Food Waste Substrates

In this study, BSFL were reared on one of the following food waste substrates namely – cabbage leaves, infested cowpea flour, infested maize flour, overripe banana peels, pineapple peels, pineapple flesh, stale bread, watermelon peels and amaranth leaves (Figure. 1). Each food waste substrate was obtained from local food markets in Ilorin, Nigeria where they had been discarded as wastes. Immediately after collection, substrates were taken to the laboratory and separately pulverized with a pestle in a small wooden mortar. Where necessary, an appropriate amount of distilled water was added to the substrate to enhance optimal larval growth. Information on description and specific processing of each substrate is outlined in Table 1. In addition to the nine substrates, chicken feed (Hybrid Feeds super starter for broilers between 0- 2 weeks old) was included as a control substrate. For every 20 g of chicken feed, 30 mL of distilled water was added to assure optimal moisture content for larval growth.

2.3 Experimental set-up

Ten 7-day larvae were introduced into plastic containers (250 mL volume and 9.5 cm base diameter) containing 20 g of a substrate type that was freshly prepared. Each plastic container and its contents were then covered with a plastic lid that was perforated for ventilation. Experiments were laid out in a completely randomized design with five replicates per substrate type (Fig. 1). On the 19th day after egg hatch (12 days after set-up), all pre-pupa were transferred from each substrate into dry plastic container (16 cm x 11.5 cm x 4.5 cm) where they pupated and emerged into adult flies. Experiments were set-up in the laboratory at the Department of Crop Protection, University of Ilorin, Ilorin, Kwara State, Nigeria (8° 30' N 4° 40.8' E) under ambient environmental conditions (29.4±0.9°C, 74.0±3.8 % R.H and 12-hour photoperiod).

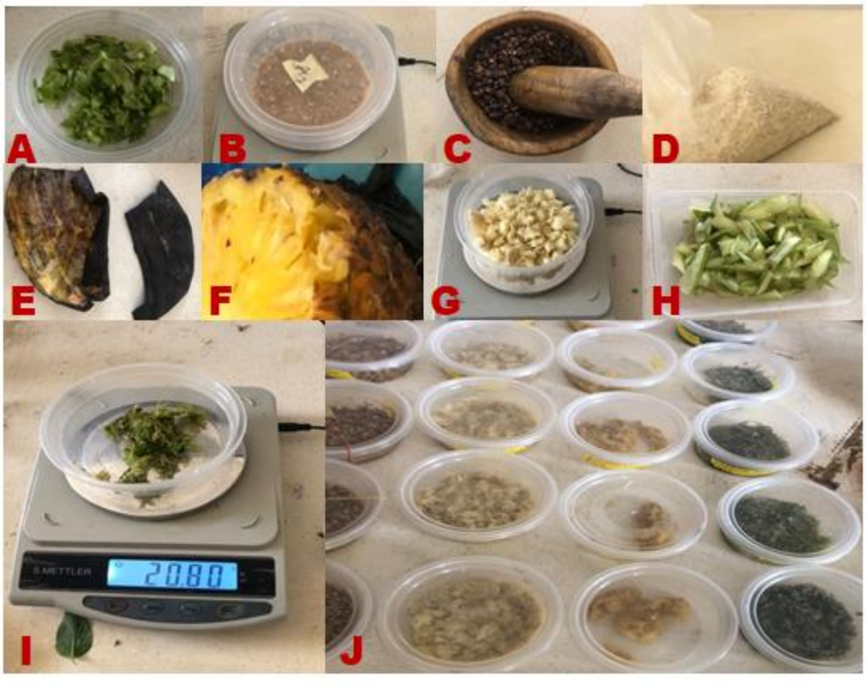

Figure 1: Food waste substrates and other experimental materials (A) Minced cabbage leaves (B) Chicken feed (C) Infested cowpea grains in a wooden mortar with pestle (D) Weevil damaged maize grains (E) Overripe banana peels (F) Pineapple with flesh and peels (G) Minced bread crumbs (H) Minced watermelon peels with rind (I) Mashed amaranth leaves being weighed on a digital (S Mettler) precision balance (J) cross section of the different substrates in plastic containers

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Table 1: Type, description and specific processing of market waste substrates used for rearing Black Soldier Fly, *Hermetia illucens* L.

Market waste substrate	Description of substrate	Specific substrate processing
Cabbage leaves	Wrinkled light-green leaves peeled off from the entire vegetable	Leaves were minced and mashed. For every 20 g of the mashed substrate, 10 mL of distilled water was added.
Infested cowpea flour	Mould infested cowpea grains	Grains were crushed into flour. For every 20 g of flour, 30 mL of distilled water was added.
Infested maize flour	Maize grains decimated by maize weevils and riddled with holes	Grains were crushed into flour. For every 20 g of flour, 30 mL of distilled water was added.
Overripe banana peels	Blackened banana peels	Peels were minced and mashed into pulp. For every 20 g of the pulpy substrate, 10 mL of distilled water was added.
Pineapple peels	Golden yellow peels of ripe pineapple	Peels were minced and mashed into pulp. No water was added to the pulpy substrate.
Pineapple flesh	Yellow flesh of ripe pineapple	Flesh was mashed into pulp. No water was added to the pulpy substrate.
Stale bread	The inner soft crumb of a week old bread loaf made from strong flour (hard wheat flour)	Crumbs were minced manually. For every 20 g of crumbs, 50 mL of distilled water was added.
Watermelon peels	Green watermelon peels with white rinds but without red flesh	Both peels and rinds were minced and mashed. No water was added to the pulpy substrate
Wilted amaranth leaves	Green leaves of wilted amaranthus vegetables	Leaves were minced and mashed. For every 20 g of the mashed substrate, 5 mL of distilled water was added.

2.4 Data Collection

At the beginning of the experiment, five larvae were sampled from each substrate treatment and weighed on a digital sensitive balance (S. Mettler; 0.01g precision). Data was thereafter collected every other day – from the second day to the twelfth day after set-up – on the percentage survival of larvae per treatment. In addition, larval body length and width were assessed on the fourth and eighth day after set-up. On the other hand, body length and width of pre-pupae was measured on the twelfth day after set-up. Furthermore, on the fourth and eighth day after set-up, five larvae were randomly sampled and weighed. Similarly, five pre-pupae were sampled and weighed on the twelfth day after-setup. After the emergence of adult, morphometric data was collected on fly body length (measured from frontoclypeal area of the head to abdomen tip); head capsule width (measured as the distance between the lateral sides of the head); thorax width; and abdominal width. Morphometrics was done using a carbon fibre composite digital caliper (0.1 mm precision).

2.5 Data Analysis

Data on survival and morphometrics was submitted to a one-way Analysis of Variance (ANOVA) test to identify statistically significant differences between substrates. Where significant differences were found, ANOVA was followed with the Tukey's Honestly Significant Difference (HSD) post hoc test at 5% level of significance. Data analyses and graphical illustrations were done in R version 4.1.2 (R Core Team, 2021).

3. Results

Table 2: Survival of Black Soldier Fly Larvae, *Hermetia Illucens* Reared on Different Substrates

Rearing Substrate	*Survival (%)					
	2 DAS	4 DAS	6 DAS	8 DAS	10 DAS	12 DAS
Cabbage leaves	62.0±4.90 c	58.0±3.74 c	58.0±5.82 c	58.0±5.82 a	58.0±5.82 ab	58.0±5.82 ab
Chicken feed	100.0±0.00 a	96.0±2.45 a	96.0±2.45 a	86.0±5.09 a	86.0±5.09 a	86.0±5.09 a
Infested cowpea flour	90.0±4.46 ab	82.0±6.62 ab	82.0±6.62 ab	78.0±5.82 a	78.0±5.82 a	78.0±5.82 a
Infested maize flour	92.0±5.82 a	92.0±5.82 a	92.0±5.82 a	88.0±7.34 a	86.0±6.77 a	86.0±6.77 a
Overripe banana peels	100.0±0.00 a	98.00±2.00 a	94.0±3.99 a	78.0±10.18 a	78.0±10.18 a	78.0±10.18 a
Pineapple flesh	68.0±4.89 bc	66.0±3.99 bc	62.0±3.74 bc	62.0±3.74 a	46.0±5.09 b	46.0±5.10 b
Pineapple peels	84.0±5.09 abc	84.0±5.09 ab	84.0±5.09 ab	82.0±4.89 a	80.0±3.16 a	80.0±3.16 a
Stale Bread	82.0±5.82 abc	78.0±4.89 abc	76.0±3.99 abc	76.0±3.99 a	72.0±6.62 ab	72.0±6.62 ab
Watermelon peels	94.0±3.99 a	92.0±3.74 a	92.0±3.74 a	78.0±8.59 a	74.0±6.77 ab	72.0±6.62 ab
Wilted amaranth leaves	84.0±6.77 abc	78.0±5.82 abc	78.0±5.82 abc	78.0±5.82 a	78.0±5.82 a	78.0±5.82 a
	$F_{9, 40}$ = 7.10	$F_{9, 40}$ = 7.81	$F_{9, 40}$ = 7.32	$F_{9, 40}$ = 2.19	$F_{9, 40}$ = 3.89	$F_{9, 40}$ = 3.92
	p<0.0001	p<0.0001	p<0.0001	p=0.045	p=0.001	p=0.001

At two days after setup, 100% survival of BSFL was observed in chicken feed and overripe banana peels (Table 2). Considerably high survival of larvae also occurred on watermelon peels (94.0±3.99%), infested maize flour (92.0±5.82%) and infested cowpea flour (90.0±4.46%). The foregoing values were significantly higher ($F_{9, 40}$ = 7.10, p<0.0001) from that recorded on cabbage leaves (62.0±4.90%). Conversely, at two days after setup, no significant difference (p>0.05) was found in the number of larvae that survived on cabbage leaves and on amaranth leaves (84.0±6.77%), or pineapple peels (84.0±5.09%), or stale bread (82.0±5.82%), or pineapple flesh (68.0±4.89%). A steady decline in percentage survival of larvae was observed from the fourth to the 12th day after setup when the larvae pre-pupated (Table 2). Within this period, BSFL survival decreased from 96.0±2.45% to 86.0±5.09% in chicken feed; 92.0±5.82% to 86.0±6.77% in infested maize flour; 98.00±2.00% to 78.0±10.18% in overripe banana peels; and from 92.0±3.74% to 72.0±6.62% in watermelon peels. In contrast, the lowest percentage survival of larvae occurred on pineapple flesh, with values of 66.0±3.99% and 46.0±5.10% on the fourth and 12th day after setup. Similarly, larvae reared on cabbage leaves had moderate survival with fairly constant percentage values from the fourth (58.0±3.74%) to 12th (58.0±5.82%) day after setup. Generally, percentage survival of BSFL on chicken feed, infested maize flour, overripe banana, or watermelon peels were statistically the same but significantly higher than on pineapple flesh or cabbage leaves at the 10th ($F_{9, 40}$ = 3.89, p=0.001) and 12th ($F_{9, 40}$ = 3.92, p=0.001) day after setup (Table 2).

Table 3: Body length and width of Black Soldier Fly, *Hermetia illucens* larva and pre-pupa reared on different substrates

Rearing Substrate	Larva				Pre-pupa Larva	
	4 DAS*		8 DAS**		12 DAS***	
	Length (mm)	Width (mm)	Length (mm)	Width (mm)	Length (mm)	Width (mm)
Cabbage leaves	11.89±0.34 abc	2.48±0.07 bcd	14.97±0.35 abc	3.24±0.08 ab	12.3±0.48 cd	2.46±0.20 e
Chicken feed	13.11±0.44 a	3.08±0.13 a	16.62±0.39 a	3.57±0.32 a	19.43±0.42 a	4.02±0.12 a
Infested cowpea flour	9.90±0.43 de	2.53±0.14 bcd	13.12±0.40 cd	2.70±0.14 bcd	14.03±0.42 bc	3.00±0.08 cde
Infested maize flour	12.29±0.34 ab	2.73±0.09 abc	15.91±0.50 a	3.01±0.12 abc	16.17±0.82 b	2.92±0.15 de
Overripe banana peels	12.59±0.35 a	2.79±0.10 ab	14.73±0.45 abc	2.92±0.11 abc	19.32±0.33 a	3.74±0.11 ab
Pineapple flesh	7.23±0.31 f	1.89±0.08 e	11.82±0.67 d	2.02±0.13 d	9.91±0.57 e	1.64±0.19 f
Pineapple peels	8.50±0.41 ef	2.11±0.11 de	11.82±0.30 d	2.50±0.16 cd	11.19±0.33 de	2.60±0.25 de
Stale Bread	10.31±0.44 cd	2.32±0.06 cde	15.74±0.34 ab	3.20±0.08 ab	15.64±0.57 b	3.14±0.08 bcd
Watermelon peels	10.56±0.38 bcd	2.58±0.05 bc	13.85±0.46 bc	2.92±0.12 abc	18.39±0.39 a	3.60±0.11 abc
Wilted amaranth leaves	10.56±0.38 bcd	2.41±0.10 bcd	13.24±0.51 cd	2.46±0.09 cd	11.65±0.25 de	2.54±0.10 de
	$F_{9, 240}$ = 23.39	$F_{9, 240}$ = 12.51	$F_{9, 240}$ = 14.47	$F_{9, 240}$ = 8.85	$F_{9, 240}$ = 52.59	$F_{9, 240}$ = 25.07
	p<0.0001	p<0.0001	p<0.0001	p<0.0001	p<0.0001	p<0.0001

Values are mean ± standard error

Values in a column followed by the same letter(s) are not significantly different (Tukey HSD test, α = 0.05)

DAS: Days After Setup

*4 DAS: Larvae were 11 days old

**8 DAS: Larvae were 15 days old

***12 DAS: Larvae were 19 days old and at the pre-pupa stage

On the fourth day after setup, larvae reared on chicken feed, overripe banana peels, and infested maize flour had the longest body length (13.11±0.44 mm, 12.59±0.35 mm and 12.29±0.34 mm) and body width (3.08±0.13 mm, 2.79±0.10 mm, and 2.73±0.09 mm), respectively (Table 3). In contrast, the shortest body lengths (8.50±0.41 mm and 7.23±0.31 mm) and body width (2.11±0.11 mm and 1.89±0.08 mm) were recorded on larvae reared on pineapple peels and pineapple flesh substrates. Significant differences were found in the length ($F_{9, 240}$ = 23.39, p<0.0001) and width ($F_{9, 240}$ = 12.51, p<0.0001) of larvae reared on pineapple peels or pineapple flesh and those of larvae reared on chicken feed, overripe banana peels, cabbage leaves, and watermelon peels at four days after setup (Table 3). Similarly, on the eighth day after setup, body length and width of larvae reared on chicken feed (16.62±0.39 mm and 3.57±0.32 mm), infested maize flour (15.91±0.50 mm and 3.01±0.12 mm), stale bread (15.74±0.34 mm and 3.20±0.08 mm), cabbage leaves (14.97±0.35 mm and 3.24±0.08 mm), and overripe banana peels (14.73±0.45 mm and 2.92±0.11 mm) were significantly longer ($F_{9, 240}$ = 14.47, p<0.0001) and wider ($F_{9, 240}$ = 8.85, p<0.0001) than those of larvae reared on pineapple flesh (11.82±0.67 mm and 2.02±0.13 mm) and pineapple peels (11.82±0.30 mm and 2.50±0.16 mm) (Table 3). Nevertheless, the highest percentage change in larval body length from the fourth to the eight day after setup was occurred in pineapple flesh (63.48%), stale bread (52.67%), pineapple peel (39.06%), infested cowpea flour (32.53%), and watermelon peels (31.16%). Similarly, larvae reared on infested cowpea flour (43.01%), stale bread (37.93%) and cabbage leaves (30.65%) had the highest change in body width between the fourth and eight day after setup (Table 3). While body length and width of larvae generally increased from the fourth to the eight day after setup irrespective of rearing substrate, body length and width of pre-pupae larvae did not increase in all substrates at the 12th day after setup (Table 3). At this period only pre-pupa larvae reared on chicken feed (19.43±0.42 mm), overripe banana peels (19.32±0.33 mm), and watermelon peels (18.39±0.39 mm) had increased body length, being significantly longer ($F_{9, 240}$ = 52.59, p<0.0001) than pre-pupa larvae reared on pineapple flesh (9.91±0.57 mm) and pineapple peels (11.19±0.33 mm).

Table 4: Weight of Black Soldier Fly Larvae, *Hermetia Illucens* Reared on Different Substrates

Rearing Substrate	Mean weight of five larvae (g)			
	Larva			Pre-pupa larva
	0 DAS	4 DAS	8 DAS	12 DAS
Cabbage leaves	0.09±0.01 a	0.52±0.01 c	1.00±0.06 abc	0.93±0.1 bc
Chicken feed	0.10±0.00 a	0.95±0.03 a	1.32±0.12 a	1.01±0.05 b
Infested cowpea flour	0.10±0.01 a	0.78±0.05 ab	0.97±0.09 abc	0.60±0.10 cd
Infested maize flour	0.13±0.03 a	0.77±0.07 ab	1.38±0.18 a	1.10±0.07 ab
Overripe banana peels	0.11±0.01 a	0.75±0.08 ab	1.27±0.12 ab	0.92±0.04 bc
Pineapple flesh	0.09±0.00 a	0.43±0.01 cd	0.50±0.17 c	0.50±0.13 d
Pineapple peels	0.10±0.01 a	0.28±0.04 d	0.56±0.09 c	0.54±0.06 d
Stale Bread	0.10±0.00 a	0.80±0.02 ab	1.24±0.05 ab	1.42±0.06 a
Watermelon peels	0.10±0.01 a	0.62±0.06 bc	0.77±0.07 bc	0.53±0.02 d
Wilted amaranth leaves	0.10±0.01 a	0.53±0.04 c	0.67±0.07 c	0.53±0.04 d
	$F_{9, 40}$ = 1.32	$F_{9, 40}$ = 19.71	$F_{9, 40}$ = 8.84	$F_{9, 40}$ = 18.34
	p = 0.259	p<0.0001	p<0.0001	p<0.0001

Values are mean ± standard error

Values in a column followed by the same letter(s) are not significantly different (Tukey HSD test, α = 0.05)

DAS: Days After Setup

*4 DAS: Larvae were 11 days old

**8 DAS: Larvae were 15 days old

***12 DAS: Larvae were 19 days old and at the pre-pupa stage

In all substrates assessed, larvae generally increased in weight from setup day to the eight day after setup (Table 4). On the fourth day after setup, larvae reared on chicken feed had the highest weight (0.95±0.03 g). Nevertheless, this mean weight value was not significantly different from those recorded for larvae reared on stale bread (0.80±0.02 g), infested cowpea flour (0.78±0.05 g), infested maize flour (0.77±0.07 g), and overripe banana peels (0.75±0.08 g). Conversely, larvae reared on pineapple peels (0.28±0.04 g) and pineapple flesh (0.43±0.01 g) had the lowest weight at four days after setup, and were significantly lighter ($F_{9, 40}$ = 19.71, p<0.0001) compared to larvae reared on chicken feed, stale bread, infested cowpea flour, infested maize flour, and overripe banana peels (Table 4). Similarly, on the eighth day after setup, significantly higher ($F_{9, 40}$ = 8.84, p<0.0001) weight values were recorded in larvae reared on infested maize flour (1.38±0.18 g), chicken feed (1.32±0.12 g), overripe banana peels (1.27±0.12 g), and stale bread (1.24±0.05 g).

Furthermore, significant differences were found in the weight of pre-pupa larval reared on the different substrates at 12 days after setup (Table 4). The highest larval weight value occurred on stale bread (1.42±0.06 g), infested maize flour (1.10±0.07 g), and chicken feed (1.01±0.05 g). These values were significantly higher ($F_{9, 40}$ = 18.34, p<0.0001) than those of larvae on pineapple peels (0.54±0.06 g), pineapple flesh (0.50±0.13 g), wilted amaranth leaves (0.53±0.04 g), and watermelon peels (0.53±0.02 g). With the exception of pre-pupa larvae on stale bread, which gained additional weight and those on pineapple flesh which experienced no weight change, larvae on all other substrates decreased in body weight at 12 days after setup (Table 4). The observed decrease in larval weight at this period caused percentage weight losses that ranged from 7.0% in larvae reared on cabbage leaves to 38.14% on infested cowpea flour (Table 4).

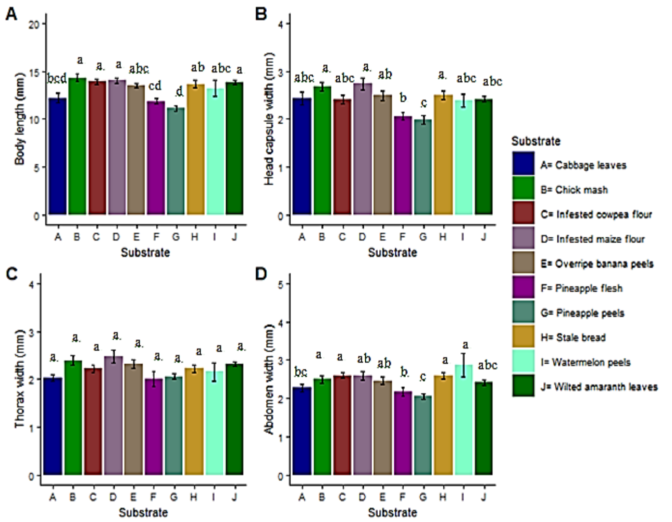

Figure 2: Morphometrics (A) body length (B) head capsule width (C) thorax width (D) abdomen width of adult Black Soldier Fly, *Hermetia illucens* that emerged from larvae reared on ten different rearing substrates.

The body length, head capsule width, thorax width and abdomen width of emerged adults varied amongst the ten substrates (Figure 2A-D). Adults from larvae reared on chicken feed (14.30±0.37 mm), infested maize flour (14.01±0.30 mm), infested cowpea flour (13.90±0.23 mm), and wilted amaranth leaves (13.82±0.24 mm) had significantly longer ($F_{9, 174}$ = 9.78, p<0.0001) bodies than adults on cabbage leaves (12.19±0.49 mm), pineapple flesh (11.84±0.28 mm), and pineapple peels (11.12±0.26 mm) (Figure 2A). Similarly, head capsule widths of adults from larvae reared on infested maize flour (2.73±0.13 mm), chicken feed (2.68±0.09 mm), and stale bread (2.50±0.10 mm) were only significantly wider ($F_{9, 174}$ = 5.17, p<0.0001) than those of adults on pineapple flesh (2.06±0.08 mm) and pineapple peels (1.98±0.09 mm) (Figure. 2B). In contrast, no significant difference ($F_{9, 174}$ = 2.46, p = 0.012) was found in the thorax widths of flies from larvae maintained on the different substrates (Figure 2C). Abdominal width of the flies (Figure 2D) were, however, significantly wider ($F_{9, 174}$ = 4.31, p<0.0001) when larvae were reared on watermelon peels (2.87±0.30 mm), infested cowpea flour (2.60±0.07 mm), stale bread (2.60±0.08 mm), and chicken feed (2.50±0.09 mm) than when maintained on cabbage leaves (2.27±0.09), pineapple flesh (2.17±0.10 mm) and pineapple peels (2.06±0.07 mm). Generally, no significant difference (p>0.05) was found in the body length, head capsule width, thorax and abdomen widths of BSFL reared on pineapple peels and cabbage leaves.

4. Discussion

Food quality significantly affects survival, size, and adult fertility of artificially reared *H. illucens* (Nguyen et al., 2013; Gobbi et al., 2013). Consequently, this study investigated the effect of common market food wastes in Nigeria including cabbage leaves, infested cowpea flour, infested maize flour, overripe banana peels, pineapple flesh, pineapple peel, stale bread, watermelon peels and amaranth leaves on larval survival, larval weight and on larval and adult body size. Larvae and adult *H. illucens* reared on chicken feed consistently had the highest survival, body size increase and weight gain. Chicken feed, such as the type used in the present study, is known to have high protein and carbohydrate contents of 18.5% and 61.81%, respectively (Ofori et al., 2019). Consequently, it is used as a high quality control or reference substrate against which the performance of other rearing substrates is checked (Spranghers et al., 2016). Like the control substrate, infested maize flour supported the survival of more than 85% of BSFL to the pre-pupae stage and was therefore very suitable for BSFL rearing. This is not unexpected since maize is a primary component of chicken feed, and is reported to contain up to 77.5% carbohydrate content (Ape et al., 2016). In contrast, less than 50% of larvae reared on pineapple flesh survived to the pre-pupa stage. This observation may be due to the moisture content of the pineapple flesh used in the present study. Pineapple flesh, the edible part of the pineapple fruit, is reported to have a high moisture content of about 87% (Bala and Bashar, 2017). Excessive moisture (above 80%) is known to result in decreased substrate degradation, and poor BSFL growth (Diener et al., 2011; Dortmans et al., 2017). Survival of BSFL on pineapple flesh may, therefore be enhanced by dewatering the pulp before use as rearing substrate. Similarly, less than 60 percent of larvae survived to the pre-pupa stage on cabbage leaves. This observation may be attributed to the physical state of cabbage leaves used in the present study. Despite being pulverized, the resultant particles were observed to be larger compared to those obtained from amaranth leaves or other waste substrates used in the study. Digestion of organic waste substrates by BSFL can be enhanced by subjecting the substrates to various particle reduction processes including crushing, milling, and grinding (Pastor et al., 2015). These processes help increase substrates' surface area and the biodegradation activities of symbiotic gut bacteria in BSFL thus improving larval growth (Jeon et al., 2011; Dortmans et al., 2017). The use of pestle and mortar for pulverization of substrates was adopted in this study as cheap grinding equipment that local farmers in Nigeria can easily access. Nevertheless, it may be necessary to use a mechanical blender for some substrates like cabbage leaves so as to enhance the production of smaller and easier to digest particles for BSFL rearing. Stale bread used in the present study was made from hard wheat flour (strong flour) which generally has crude protein and carbohydrate of about 13% and 63.0%, respectively (Mongi et al., 2011). Despite having similar high protein and carbohydrate contents as chicken feed and maize flours, survival of BSFL on stale bread was not as high as the two aforementioned substrates. Sodium chloride is an important ingredient that is often added in relatively small amounts when making bread. Several authors (Cho et al., 2020, Kwon and Kim, 2016) have however shown that sodium chloride concentrations in rearing substrates can significantly inhibit the survival, growth and development of BSFL. The presence of sodium chloride in the stale bread may, to some extent, be responsible for the sub-optimal survival of BSFL on the substrate in the present study.

The ability of *H. illucens* to utilize different biowaste streams for growth and development (Cammack and Tomberlin, 2017) is affirmed in the present study by the general increase in BSFL length, width and weight on all evaluated food waste substrates. Nevertheless, significant differences were observed in the size and weight of *H. illucens* reared on the different substrates types. These differences may be attributed to variations in substrates' nutritional composition, which have been reported by several authors. For instance, protein and carbohydrate contents were respectively reported to be 18.5% and 61.81% in chick feed (Ofori et al., 2019); 8.75% and 77.46% in maize flour (Ape et al., 2016); 12.54% and 63.25% in bread (Mongi et al., 2011); and 19.71% and 57.17% in cowpea flour (Ilesanmi and Gungula, 2016). Similarly, protein and carbohydrate contents were reported as 10.44% and 43.40% in banana peels (Feumba et al., 2016); 12.42% and 32.16% in watermelon peels (Feumba et al., 2016); 12.86% and 9.06% in amaranthus leaves (Akinnibosun and Adeola, 2015). Protein and carbohydrate content was respectively 3.0% and 82.57% in pineapple flesh or pulp (Bala and Bashar, 2017); 5.11% and 55.52% in pineapple peels (Feumba et al., 2016); and 1.94% and 4.52% in cabbage leaves (Ogbede et al., 2015). Generally, *H. illucens* larvae and adults reared on cabbage leaves, pineapple flesh, and pineapple peels substrates with relatively low protein content performed poorly with regards to increase in body length, width and or weight. The foregoing observation highlights the importance of protein as a key nutrient for BSFL development. According to Oonincx et al. (2015), survival and development of BSFL was faster on protein-rich food waste diets. Similarly, Cammack and Tomberlin (2017) also reported significantly faster BSFL development on artificial diets with equal proportion of protein and carbohydrate. On the other hand, despite maintaining a constant carbohydrate content level, protracted development of the Mediterranean fruit fly, *Ceratitis capitata* larvae occurred when rearing diet was low in protein (Nash and Chapman, 2014). The secondary place of carbohydrate in *H. illucens* is further highlighted in the present study by the significantly lower body length, body width, and body weight of larvae reared on pineapple peels and pineapple flesh both of which are considerably high in carbohydrate but very low in protein (Feumba et al., 2016; Bala and Bashar, 2017). The use of published secondary data on the nutritional composition of substrates may pose some limitation to the inferences made about substrate suitability in the present study. Future studies should therefore include a proximate analysis component to ascertain the exact nutritional composition of each substrate (Spranghers et al., 2016). In addition, a mix of these common market food wastes in Nigeria and their suitability for optimal survival, growth and development of *H. illucens* should be investigated in future research studies.

5. Conclusions

The potential of the black soldier fly larvae to valorize a wide range of organic waste streams offers an efficient and environmentally friendly approach for municipal organic waste management. It also provides a sustainable method for the production of high quality alternative protein for livestock feed and organic compost for crop production. In this study the effect of common market food waste substrates in Nigeria on the survival, and morphometrics of black soldier fly larvae and adults was investigated. Survival and body measurements were generally higher in *H. illucens* reared on the control chicken feed, infested maize flour, stale bread substrates, cowpea flour, and banana peels. In contrast, *H. illucens* survival and body morphometrics was lowest on pineapple flesh, pineapple peels, and cabbage leaves. Information provided in this study will enhance selection of suitable market food wastes for low-cost production of black soldier fly larvae in Nigeria.

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