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ORIGINAL ARTICLE

ASSESSMENT OF BLACK SOLDIER FLY LARVAE PERFORMANCE IN VALORISATION OF DIFFERENT ORGANIC WASTES

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ABSTRACT
The study evaluated the performance of Hermetia illucens larvae in the bioconversion of different organic wastes, including pig waste, poultry waste, kitchen waste, and combinations thereof, over 18 days. Larval growth and residual waste were monitored at 1, 6, 12, and 18 days after introduction (DAI). Initial larval weights were uniform across treatments (25 g), with similar starting waste quantities (1200 g). By 18 DAI, larvae reared on pig waste alone achieved the highest biomass (527.27±25.86 g), followed by kitchen waste alone (465.45 ± 4.20 g), whereas poultry waste alone produced the lowest biomass (249.09±4.51 g). Residual waste was lowest in pig waste (210.91±5.05 g) and kitchen waste (272.73±2.87 g) treatments, indicating efficient substrate conversion, while poultry waste remained highest (659.00 ± 9.50 g). Mixed substrates (pig + kitchen, poultry + kitchen) yielded intermediate results. Cumulative data confirmed that both substrate type and feeding duration significantly influenced larval growth and waste reduction. The results highlight the potential of H. illucens as a sustainable tool for organic waste valorisation, producing protein-rich larvae and nutrient-rich frass. These findings provide guidance for the design of BSFL-based bioconversion systems for sustainable waste management and agricultural applications.
KEYWORDS: *Substrate, nutrient recovery, circular economy, bioconversion efficiency.*

INTRODUCTION

In 2019, the world generated approximately 931 million tons of food waste (Statista, 2023a). With predicted population growth, urbanization, and economic development, global municipal waste generation is expected to increase in 2050 by 70% (Statista, 2023b). Globally, around half of municipal waste is organic (World Bank, 2023). Despite the availability of alternative management options, majority of organic waste worldwide is either openly dumped (31%) or placed in landfills (37%), according to World Bank (2023). Disposing of organic waste in open dumps or landfills can result in the spread of diseases and pests, methane gas emissions, landscape deterioration, and odour pollution (Siddiqua *et al*., 2022). Organic waste management is a multi-dimensional challenge involving technical, economic, political, socio-cultural, organizational, and environmental issues (Guerrero *et al.*, 2013). According to Kharola *et al*. (2022), several barriers hinder sustainable management of organic waste, including lack of communication, planning, financial resources, technology, and infrastructure. At the top of their list of solutions to poor organic waste management is the creation of value from waste. Several waste management systems demonstrate this approach (Lalander *et al.,* 2018). Conventional composting produces organic fertilizer, while anaerobic digestion produces both organic fertilizer and biogas, which can be used to generate electricity or serve as vehicle fuel (Tominac *et al.*, 2021).

However, conventional composting presents challenges such as the risk of methane emissions and odour pollution (Ayilara *et al.*, 2020). Anaerobic digestion, on the other hand, involves high financial costs and requires highly trained personnel to ensure proper process control (Xu *et al.*, 2018). Black soldier fly (*Hermetia illucens*) larvae (BSFL) composting is another promising option for creating value from waste (Tomberlin and van Huis, 2020). This process produces larvae, which can be used in animal feed or processed into fuel, as well as an organic fertilizer. Interest in BSFL composting has increased significantly over the past decade (Tomberlin and van Huis, 2020), mainly due to its financial viability as an organic waste management strategy with relatively low investment costs—an especially important factor in low- and middle-income countries (Purkayastha and Sarkar, 2022). The performance of BSFL varies depending on substrate type, nutrient composition, and moisture content. While *H. illucens* is highly efficient, other insect species larvae performance, such as housefly (*Musca domestica*) larvae and yellow mealworm (*Tenebrio molitor*), has also been investigated for organic waste conversion, albeit with varying efficiency and substrate specificity (Gold *et al.,* 2018). Comparative studies indicate that substrate quality and nutritional balance critically affect larval growth, waste reduction, and the biochemical composition of harvested biomass.

Understanding the influence of substrate type and feeding duration on BSFL growth and waste reduction is essential for optimizing organic waste valorisation systems. Despite growing research on BSFL, comprehensive assessments of different organic wastes, including pig, poultry, kitchen wastes, and their combinations, remain limited, particularly in terms of cumulative larval growth and waste conversion efficiency over time. Thus, the aim of this research is to comparatively assess the performance of different organic wastes in BSFL composting.

MATERIALS AND METHODS

The study was conducted at a BSFL composting facility located within University Park, University of Port Harcourt, Nigeria. The facility has the capacity to process approximately 2 tons of organic waste per day, consisting mainly of fruits, vegetables, and livestock droppings. Temperature, relative humidity, and exposure to direct sunlight were primarily influenced by prevailing weather conditions due to the facility's semi-open construction.

Plate 1: Black soldier fly love net

Plate 2: Black soldier fly larvae on substrate

The facility was divided into the following areas: waste pre-processing, treatment, BSF colony, harvest, larvae refining, and compost processing. The BSF colony included puparia areas, where flies emerged from pupae, and a greenhouse, where mating, egg-laying, and hatching occurred. All the sections were partially enclosed with mesh on the sides to protect insect production from birds and other pests. The treatment and puparium areas were covered with metal roofs to protect against rain and direct sunlight, while the greenhouse had a combination of plastic and net roofing that provided rain protection while allowing sunlight penetration. Mesh cages containing BSF-nets (plate 1) and the nursery were both placed inside the greenhouse.

Five treatment combinations were used: pig waste alone, poultry + kitchen waste, poultry waste alone, kitchen waste alone, and pig + kitchen waste. Each treatment weighed 1,200g. Larvae (plate 2) weighing 25g each were placed in circular bowls (280g each) and introduced to the respective substrates. Each bowl was covered with netting to prevent larval escape and protect against predators. The experiment followed a completely randomised design with six replications, making a total of 30 bowls. Larvae and waste were harvested and weighed weekly, with values recorded accordingly. The mean values obtained were subjected to analysis of variance at a 5% significance level ($P<0.05$), and means were separated using Duncan's Multiple Range Test. A Pearson correlation test was also conducted on the mean values of waste weight and larval weight to determine the relationship between them. The experiment was terminated after 4 weeks.

RESULTS

Mean larval weight of Hermetia illucens at 1 and 6 Days after Introduction under different organic waste treatments

At 1 day after introduction (1 DAI), larval weight and waste weight were uniform across all treatments (Table 1) Initial larval weight was 25.00g in all treatments, with only minor variation, while waste weight was approximately 1200g for each treatment. At 6 days after introduction (6 DAI), significant differences were observed among treatments in larval weight and residual waste weight. Larval weight ranged from 90.91±1.94g to 172.73±4.31g, while residual waste weight ranged from 872.73±3.61g to 1127.27±5.90g.

Table 1: Mean larval weight (g) of *Hermetia illucens* at 1 and 6 Days after Introduction under different organic waste treatments

Treatment	1 DAI		6 DAI	
	Weight of larvae	Weight of waste	Weight of larvae	Weight of waste
Pig waste alone	25.00±2.00	1200.00±11.00	172.73±4.31^{d}	927.27±7.52^{b}
Poultry + Kitchen waste	25.00±3.00	1200.00±9.00	106.82±0.52^{b}	1123.86±4.62^{c}
Poultry waste alone	25.00±5.00	1200.00±12.00	90.91±1.94^{a}	1127.27±5.90^{c}
Kitchen waste alone	25.00±1.00	1200.00±2.00	154.55±5.08^{c}	927.27±7.41^{b}
Pig + Kitchen waste	25.00±3.00	1200.00±4.00	104.55±4.73^{b}	872.73±3.61^{a}

Results are expressed as mean ± standard deviation, n = 3. Mean values with different alphabets as superscripts down the column are significantly ($p<0.05$) different according to Duncan's Multiple Range Test (DMRT). DAI = Days after Introduction

The pig waste alone treatment recorded the highest larval weight (172.73±4.31g) and a residual waste weight of 927.27±7.52g. The kitchen waste alone treatment produced a larval weight of 154.55±5.08g with a residual waste weight of 927.27±7.41g. Larval weights of 106.82±0.52g and 104.55±4.73g were recorded for poultry + kitchen waste and pig + kitchen waste, respectively, while poultry waste alone resulted in the lowest larval weight (90.91±1.94g). Residual waste weights were highest in the poultry waste alone (1127.27±5.90g) and poultry + kitchen waste (1123.86±4.62g) treatments, whereas the lowest residual waste weight was observed in the pig + kitchen waste treatment (872.73±3.61g).

Mean larval weight of **Hermetia illucens** *at 12 and 18 Days after Introduction under different organic waste treatments*

At 12 days after introduction (12 DAI), larval weight differed significantly among treatments. The highest larval weight was recorded in the pig waste alone treatment (350.00±3.00g), followed by kitchen waste alone (310.00±6.60g) as shown in Table 2. Intermediate larval weights were observed in the poultry + kitchen waste (205.00±5.60g) and pig + kitchen waste (200.00±1.20g) treatments, while the lowest larval weight occurred in the poultry waste alone treatment (170.00±5.80g).

Residual waste weight at 12 DAI also varied significantly across treatments. The lowest residual waste weight was observed in the pig + kitchen waste treatment (480.00±2.72g), followed by pig waste alone (560.00±8.00g). Higher residual waste weights were recorded in kitchen waste alone (600.00±6.50g) and poultry waste alone (659.09±6.88g), while the highest residual waste weight was observed in the poultry + kitchen waste treatment (850.00±10.50g). At 18 days after introduction (18 DAI), larval weight increased further in all treatments, with significant differences remaining among substrates. The pig waste alone treatment recorded the highest larval weight (527.27±25.86g), followed by kitchen waste alone (465.45±4.20g). The poultry + kitchen waste (303.09±4.20g) and pig + kitchen waste (295.45±5.47g) treatments showed intermediate larval weights, while poultry waste alone remained the lowest (249.09±4.51g).

Table 2: Mean larval weight (g) of *Hermetia illucens* at 12 and 18 Days after Introduction under different organic waste treatments

Treatment	12 DAI		18 DAI	
	Weight of larvae	Weight of waste	Weight of larvae	Weight of waste
Pig waste alone	350.00±3.00^{d}	560.00±8.00^{b}	527.27±25.86^{d}	210.91±5.05^{a}
Poultry + Kitchen waste	205.00±5.60^{b}	850.00±10.50^{e}	303.09±4.20^{b}	496.36±5.12^{c}
Poultry waste alone	170.00±5.80^{a}	659.09±6.88^{d}	249.09±4.51^{a}	659.00±9.50^{e}
Kitchen waste alone	310.00±6.60^{c}	600.00±6.50^{c}	465.45±4.20^{c}	272.73±2.87^{b}
Pig + Kitchen waste	200.00±1.20^{b}	480.00±2.72^{a}	295.45±5.47^{b}	542.12±2.34^{d}

Results are expressed as mean ± standard deviation, n = 3. Mean values with different alphabets as superscripts down the column are significantly (p<0.05) different according to Duncan's Multiple Range Test (DMRT). DAI = Days after Introduction

Residual waste weight at 18 DAI showed a clear reduction relative to 12 DAI in most treatments. The lowest residual waste weight was recorded in the pig waste alone treatment (210.91±5.05g), followed by kitchen waste alone (272.73±2.87g). Higher residual waste weights were observed in the poultry + kitchen waste (496.36±5.12g) and pig + kitchen waste (542.12±2.34 g) treatments, while the highest residual waste weight remained in the poultry waste alone treatment (659.00±9.50g).

Cumulative effect of treatment on weight (g) of larvae and waste respectively

The cumulative larval weight differed significantly among treatments. The highest cumulative larval weight was recorded in the pig waste alone treatment (268.75±197.16g), followed by kitchen waste alone (238.75±172.66g). Intermediate cumulative larval weights were observed in the poultry + kitchen waste (159.98±109.04g) and pig + kitchen waste (156.25±106.04g) treatments, while the lowest cumulative larval weight was recorded in the poultry waste alone treatment (133.75±87.91g).

Table 3: Cumulative effect of treatment on weight (g) of larvae and waste respectively

Treatments	Weight of larvae	Weight of waste
Pig waste alone	268.75±197.16^{d}	724.55±390.18^{a}
Poultry + Kitchen waste	159.98±109.04^{b}	917.56±288.16^{e}
Poultry waste alone	133.75±87.91^{a}	911.34±264.99^{d}
Kitchen waste alone	238.75±172.66^{c}	750.00±363.42^{b}
Pig + Kitchen waste	156.25±106.04^{b}	773.71±300.66^{c}

Results are expressed as mean ± standard deviation, n = 3. Mean values with different alphabets as superscripts down the column are significantly (p<0.05) different according to Duncan's Multiple Range Test (DMRT). DAI = Days after Introduction

Cumulative waste weight also showed significant variation across treatments. The highest cumulative waste weight was observed in the poultry + kitchen waste treatment (917.56±288.16g), closely followed by poultry waste alone (911.34±264.99g). Lower cumulative waste weights were recorded in the pig + kitchen waste (773.71±300.66g) and kitchen waste alone (750.00±363.42g) treatments, while the pig waste alone treatment recorded the lowest cumulative waste weight (724.55±390.18g).

Cumulative effect of Treatments on weight (g) of larvae and waste with respect to Days after Introduction

Larval weight and residual waste weight changed markedly over time, reflecting progressive feeding and growth of *Hermetia illucens* larvae. At **1 day after introduction (1 DAI)**, larval weight was lowest (25.00±2.62g) and residual waste was highest (1200.00±7.23g), indicating minimal feeding and substrate conversion at the start of the experiment as shown in Table 4. However, at **6 DAI**, larval weight had increased to 125.91±33.08g, while residual waste decreased to 995.68±111.81g, demonstrating early larval growth and waste consumption. At 12 DAI, larval weight rose further to 247.00±72.54g, with a corresponding reduction in residual waste to 629.82±129.06g, reflecting substantial bioconversion of the substrate. Lastly, at 18 DAI, larval weight reached 368.07±112.42g, while residual waste declined to 436.22±174.47g, representing the highest cumulative larval biomass and lowest waste mass over the experimental period.

Table 4: Cumulative effect of Treatments on weight (g) of larvae and waste with respect to Days after Introduction

Duration	Weight of larvae	Weight of waste
1 DAI	25.00 ± 2.62^{a}	1200.00 ± 7.23^{d}
6 DAI	125.91 ± 33.08^{b}	995.68 ± 111.81^{c}
12 DAI	247.00 ± 72.54^{c}	629.82 ± 129.06^{b}
18 DAI	368.07 ± 112.42^{d}	436.22 ± 174.47^{a}

Results are expressed as mean ± standard deviation, n = 3. Mean values with different alphabets as superscripts down the column are significantly ($p<0.05$) different according to Duncan's Multiple Range Test (DMRT). DAI = Days after Introduction

DISCUSSION

Mean larval weight of Hermetia illucens at 1 and 6 Days after Introduction under different organic waste treatments

The results demonstrate that substrate type significantly influenced both larval biomass accumulation and waste reduction efficiency of *Hermetia illucens* over the six-day rearing period. The uniform larval and waste weights observed at 1 DAI confirm that all treatments began under comparable conditions, validating those differences recorded at 6 DAI were attributable to substrate composition rather than initial variability. At 6 DAI, larvae reared on pig waste alone achieved the highest biomass. This agrees with previous studies reporting that pig manure supports superior BSFL growth due to its relatively balanced protein content, favourable moisture level, and readily degradable organic matter, which enhance larval feeding and assimilation efficiency (Diener *et al.*, 2009). The substantial reduction in waste mass under this treatment further indicates efficient bioconversion of pig waste by the larvae.

Similarly, kitchen waste alone supported high larval growth, ranking second after pig waste. Kitchen waste is typically rich in carbohydrates, lipids, and easily degradable organic fractions, which are rapidly utilized by BSFL, resulting in accelerated biomass accumulation (Myers *et al.*, 2008). The comparable residual waste weight observed in both pig waste and kitchen waste treatments suggests similar levels of waste degradation efficiency, despite differences in nutrient composition. In contrast, poultry waste alone resulted in the lowest larval weight and among the highest residual waste weights. Poultry manure is often characterized by high nitrogen content and elevated ammonia levels, which can negatively affect larval survival, feeding activity, and growth performance (Sheppard *et al.*, 2002). The limited reduction in waste mass observed under this treatment indicates reduced larval feeding efficiency and substrate utilization.

The mixed waste treatments (poultry + kitchen waste and pig + kitchen waste) produced intermediate larval weights, reflecting the moderating effect of substrate blending. Co-substrating has been reported to improve physical structure, dilute inhibitory compounds, and balance nutrient ratios, thereby enhancing overall waste degradation (Lalander *et al*., 2015). Notably, the pig + kitchen waste treatment recorded the lowest residual waste weight, indicating the highest waste reduction efficiency, even though larval biomass gain was not maximal. This observation supports earlier findings that waste reduction efficiency and larval biomass accumulation are not always directly proportional, as larvae may allocate assimilated nutrients toward metabolism and maintenance rather than somatic growth depending on substrate characteristics (Diener *et al.*, 2011). Overall, the findings confirm that BSFL performance is highly substrate-dependent. Single substrates such as pig waste and kitchen waste favoured larval biomass accumulation, whereas mixed substrates—particularly pig + kitchen waste—enhanced waste reduction efficiency. These results underscore the importance of substrate selection and optimization in BSFL-based organic waste valorisation systems and are consistent with established literature on insect-based bioconversion of organic residues.

Mean larval weight of Hermetia illucens at 12 and 18 Days after Introduction under different organic waste treatments

The results at 12 and 18 days after introduction (DAI) clearly demonstrate that substrate type strongly influenced larval biomass accumulation and waste reduction efficiency of *Hermetia illucens* over time. Across all treatments, larval weight increased from 12 to 18 DAI, accompanied by a general decline in residual waste weight, indicating continued feeding activity and progressive bioconversion of the substrates. At both 12 and 18 DAI, pig waste alone consistently supported the highest larval weights and the lowest residual waste weights by the end of the rearing period. This confirms pig waste as a highly suitable substrate for BSFL growth and waste reduction. Previous studies have shown that pig manure contains balanced levels of protein, energy, and moisture, which favour larval development and efficient nutrient assimilation (Lalander *et al.*, 2019). The substantial reduction in waste mass by 18 DAI further reflects effective substrate utilization and conversion into larval biomass. Kitchen waste alone also supported strong larval performance, ranking second to pig waste in larval biomass at both sampling periods. Kitchen waste is typically rich in readily degradable organic matter, including carbohydrates and lipids, which enhances larval growth and accelerates substrate breakdown (Gold *et al.*, 2018). The relatively low residual waste weight recorded at 18 DAI indicates efficient waste degradation comparable to pig waste, although larval biomass remained slightly lower.

In contrast**,** poultry waste alone consistently resulted in the lowest larval weights and the highest residual waste weights at both 12 and 18 DAI. This pattern suggests limited larval growth and reduced waste conversion efficiency. Poultry manure is often characterized by high nitrogen content and elevated ammonia levels, which can negatively affect larval feeding activity, growth rate, and survival (Alattar *et al.*, 2016). The persistence of high residual waste weight at 18 DAI indicates slower substrate degradation under this treatment. The mixed substrate treatments (poultry + kitchen waste and pig + kitchen waste) showed intermediate performance in terms of larval growth and waste reduction. Blending substrates generally improved outcomes relative to poultry waste alone, indicating that co-substrating can mitigate the limitations of nutritionally imbalanced or inhibitory substrates (Barragán-Fonseca *et al.*, 2017). Notably, while the pig + kitchen waste treatment recorded low residual waste weight at 12 DAI, waste reduction was less pronounced by 18 DAI compared to pig waste alone, suggesting differences in degradation dynamics and nutrient availability over time. Overall, the results indicate that larval biomass accumulation and waste reduction efficiency increased with rearing duration but varied significantly depending on substrate composition. Pig waste and kitchen waste were most effective in promoting larval growth and waste conversion, whereas poultry waste alone consistently limited performance. These findings reinforce the importance of substrate selection and optimization in BSFL-based organic waste valorisation systems.

Cumulative effect of treatment on weight of larvae and waste respectively

The cumulative results indicate that treatment type had a pronounced influence on both larval biomass accumulation and residual waste mass, confirming the substrate-dependent performance of *Hermetia illucens* larvae over the entire experimental period. The pig waste alone treatment produced the highest cumulative larval weight and the lowest cumulative waste weight. This combination reflects superior larval growth alongside efficient waste reduction. Similar outcomes have been widely reported in BSFL studies, where pig manure consistently supports enhanced larval development and effective bioconversion due to its balanced nutrient composition, suitable moisture content, and high proportion of readily degradable organic matter (Tschirner and Simon, 2015). The relatively low cumulative waste weight further suggests sustained larval feeding activity throughout the rearing period. The kitchen waste alone treatment also resulted in high cumulative larval biomass, second only to pig waste, with a comparatively low cumulative waste weight. Kitchen waste is typically rich in carbohydrates, lipids, and easily decomposable organic fractions, which are rapidly assimilated by BSFL and translated into larval biomass (Tambeayuk *et al*., 2023). The relatively large standard deviation observed reflects variability inherent in heterogeneous household waste streams, a trend commonly noted in similar studies.

In contrast, poultry waste alone yielded the lowest cumulative larval weight and one of the highest cumulative waste weights, indicating limited larval growth and inefficient waste conversion. Poultry manure is often characterized by high nitrogen content and elevated ammonia concentrations, which can suppress larval feeding efficiency and growth performance (Kalová and Borkovcová, 2013). The persistence of high residual waste mass in this treatment suggests reduced substrate utilization over time. The mixed waste treatments (poultry + kitchen waste and pig + kitchen waste) produced intermediate cumulative larval weights and waste reductions. Blending poultry waste with kitchen waste improved larval performance relative to poultry waste alone, indicating that co-substrating can dilute inhibitory compounds and improve substrate palatability and structure (Parodi *et al*., 2021). However, cumulative larval weights in mixed treatments remained lower than those observed in pig waste or kitchen waste alone, suggesting that substrate blending moderated, but did not fully optimize, growth conditions. Overall, the cumulative results demonstrate that substrates rich in easily degradable organic matter and balanced nutrients favoured larval biomass accumulation and waste reduction, whereas substrates with potential inhibitory characteristics constrained performance. These findings reinforce the importance of substrate selection and management in optimizing BSFL-based organic waste valorisation systems and are consistent with established literature on insect-mediated bioconversion of organic residues.

CONCLUSION AND RECOMMENDATIONS

The study demonstrates that both substrate type and feeding duration significantly influence the growth of *Hermetia illucens* larvae and the efficiency of organic waste reduction. Pig waste and kitchen waste, whether alone or in combination, consistently supported higher larval biomass and greater waste reduction, whereas poultry waste alone was the least effective. Larval biomass and waste conversion increased progressively over time, reaching maximum efficiency at 18 days after introduction. These findings indicate that optimizing substrate composition and allowing sufficient larval development time are critical for maximizing the dual benefits of high-protein larval biomass production and efficient organic waste valorisation. Overall, *H. illucens* demonstrates strong potential as a sustainable tool for bioconversion of diverse organic waste streams into valuable protein-rich biomass and nutrient-rich frass for agricultural applications.

Pig waste and kitchen waste are recommended as primary substrates for *Hermetia illucens* rearing due to their high larval growth potential and efficient waste reduction. Poultry waste should be blended with other substrates to mitigate its inhibitory effects on larval performance. Mixing substrates, such as pig + kitchen waste or poultry + kitchen waste, can improve waste conversion efficiency and reduce the negative effects of nutrient imbalances or inhibitory compounds. Further studies should explore ideal substrate ratios for maximizing both larval yield and waste reduction. The findings support the implementation of BSFL systems for sustainable organic waste management. Agricultural and municipal waste streams rich in degradable organic matter can be efficiently converted into protein-rich larvae for feed and nutrient-rich frass for soil amendment.

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