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Enhancement of Black Soldier Fly (*Hermetia Illucens*) Production for Organic Waste Management

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ABSTRACT

Addressing sustainable management of faecal matter has become one of the most pressing challenges of our time. It's a global issue that demands attention and innovative solutions. One such innovative solution is utilizing black soldier fly (BSF) technology, which enables bioconversion of faecal matter into valuable resources. In this study, we assessed the oviposition performance of BSF, and the adult emergence rates under different conditions. To achieve this, three feed substrates; faecal matter (FM), kitchen waste (KW), and a FM: KW at a ratio of 1:1. We also tested colour preference on oviposition performance using three flexible plastic tubes, coloured white, yellow, blue, and black as oviposition structures. Three cages of dimensions 2.5m × 1.2 m, 2m × 1 m, and 1m × 1m were used for oviposition and adult emergence tests, whereas flexible plastic tubes were used to collect eggs for comparative purposes. Approximately one kilogram of each substrate was placed into each feeding tray measuring 26 cm × 13 cm × 11 cm with 5 g of five 5-day-old larvae added, and monitored until the pupa stage, after which adult emergence and oviposition were determined. The results indicated that BSF fed on FM: KW at a ratio of1:1had the highest egg production ($P < 0.05$) (9.38 g) whereas FM and KW attained 4.65g and 5.22 g, respectively. Additionally, 2.5m × 1.2 m cage size was found to be most effective for oviposition ($P < 0.05$), at 16.38 g of eggs compared to 1 m ×1 m at 4.53 g. However, cage size had no impact on adult emergence ($P> 0.5$). The results also showed that a black-coloured egg tube was the most preferred site for oviposition. Our findings clarify further effective and economical methods to boost the production of BSF, handle and recycle wastes from onsite facilities and retrieve resources that can be utilized as animal feed and organic fertilizer.

Introduction

Safe and equitable sanitation is essential for public health, hygiene, environmental protection, and community well-being, yet globally more people rely on on-site sanitation systems (57%) than sewer connections (42%), and about 44% of faecal waste from these non-sewered systems is discharged without safe treatment, causing environmental pollution and health risks (WHO/UNICEF, 2023) Safe and equitable sanitation is essential for advancing health, good hygiene, environmental protection, and community well-being. Similarly, the management of food waste (FW) poses another significant challenge, as decomposing food releases methane, a potent

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greenhouse gas that accelerates climate change (Tamasiga *et al*., 2022). Together, these issues highlight the urgent need for innovative and sustainable waste management solutions that address both faecal and food waste streams. The development of ecological sanitation approaches has provided safe faecal waste management alternatives and at the same time an approach to recover resources and nutrients (Nhamo *et al*., 2024). For example, container-based sanitation (CBS) consists of an end-to-end service in which toilets collect excreta in sealable, removable containers. The urine and faeces are separately collected through the urine-diverting dehydrating Toilet (UDDT) model. Cover materials like lime, ash, or sawdust are added after every use to keep the faeces dry and odour-free (Riungu *et al*., 2018). However, adding the cover materials to the CBS collected faecal is not adequate for pathogen inactivation, thus requiring a post-treatment step before reuse or disposal. Technologies such as anaerobic digestion, lime addition, sun drying, drying beds and Black Soldier Fly, *Hermetia illucens* (BSF) are used to manage onsite accumulated faecal matter (Mwamlima *et al*., 2025).

The BSF larvae (BSFL) possess an impressive ability to consume a wide range of organic materials, including faecal matter, animal manure, agricultural waste, and by-products from breweries (Rehman *et al*., 2023). The larvae contain high levels of protein (up to 50% depending on rearing substrate (Bonomini *et al*., 2024), making them suitable for use in fish and poultry feed. Other by-products of this bioconversion are larval biomass, used as protein supplement and a nutrient-rich residue known as frass used as a bio-fertilizer (Surendra *et al*., 2020). With BSF, the bioconversion of waste into larval biomass occurs exclusively during the larval stage, and therefore, to ensure a continuous supply of larvae, it is essential to enhance the production of other developmental stages. BSFL require essential nutrients to support their performance, growth, and overall development. Research has shown that the growth and development of BSFL can be enhanced if these nutrient-deficient wastes are supplemented with affordable, nutrient-rich substrates such as food waste and soybean curd residues (Siddiqui *et al*., 2022). Supplementing faecal matter with kitchen waste at a 1:1 ratio resulted in increased pre-pupal weight and more favourable conditions for effective BSF performance (Achieng *et al*., 2023). Accumulating enough energy during the larval stage ensures adult survival and fecundity in the post-feeding stages (Dzepe *et al*., 2020).

The spatial and oviposition (process by which female BSF deposit their eggs), requirements of BSF present significant challenges in optimizing their production. Julita *et al*. (2020) noted that that rearing adult BSF within cages measuring approximately 45 × 45 × 45 cm (0.091 m^3) significantly enhanced egg production, yielding up to 7.8 g of eggs per oviposition period. Park *et al*. (2016) demonstrated that cage size (1.0 × 1.0 × 2.5 m to 2.5 × 2.5 × 2.5 m) had little effect on egg production, whereas adult density was the key factor influencing oviposition of BSF.

There is therefore need for adequate space to allow egg production efficiencies in cages as observed in natural populations of BSF. It is likely that inadequate mating enclosures may not allow for natural mating and thus pose a production efficiency concern (Barrett *et al*., 2023). Adult BSF tends to approach the ovipositing material from a distance and land upon it once within the range (Banks *et al*., 2025). This behaviour is predisposed by background characteristics such as light and colour influence on the eye receptors. It is essential to attract and encourage BSF to lay as many eggs as possible, particularly in controlled environments, since differences in ovitraps structure significantly affect the oviposition preference behaviour of BSF (Bryukhanov *et al*., 2022). Therefore, BSF production enhancement strategies are needed for the effective rearing, which can help manage, recycle, and recover nutrients from faecal matter and other organic wastes. This would ensure safe sanitation, limit environmental pollution, and promote sustainable economic growth. Although on-site sanitation is widely used, only a small fraction of faecal sludge is safely treated, contributing to environmental pollution and health risks. Similarly, organic waste is largely underutilized due to low recycling rates and disposal challenges. While the Black Soldier Fly (BSF) shows promise for waste management, enhancing its reproduction under controlled, conditions remain insufficiently characterized. This study experimentally tested the effects of oviposition structure colour, cage size, and feed substrate on adult emergence and oviposition performance of BSF.

Matherials and Methods

Study site

The study was conducted at the Sanitation Research Institute- Meru University of Science and Technology (SRI - MUST). SRI-MUST is located in Nkomo location in Tigania West Sub-County in Meru County, Kenya. This is a small-scale institutional BSF rearing facility. Five-day-old BSFLs were acquired from the SRI MUST rearing unit.

Bioassays

Organic waste used as feeding substrates for the larvae included: kitchen waste (KW), faecal waste (FM) and a mixture of kitchen waste and faecal matter. Rearing cage of sizes 1 × 1 m, 2 × 1 m, and 2.5 × 1.2 m were used to assess the effect of space on adult emergence and oviposition of BSF. These dimensions were selected based on prior studies indicating variability in rearing spaces. The chosen range enabled evaluation of how increased space affects adult emergence and oviposition, while remaining practical for controlled rearing conditions. Four flexible cylindrical plastic pipes of different colours (black, white, yellow and blue measuring 10 cm length × 3 cm internal diameter) were used as oviposition structures. Plastic trays measuring 26 cm × 13 cm × 11 cm were utilized as treatment chambers while an analytical balance (±0.001 g) was used to weigh eggs.

Faecal matter and kitchen waste collection

Feacal matter was collected from a CBS facility using a 20-liter bucket, with approximately 10 grams of wheat bran added after each use for odour control. The containers were collected daily, and swapped with clean ones. The containers were then transported to SRI faecal matter conversion unit where the content therein was transferred to a 100litre container and mixed thoroughly with a wooden rod to create a homogenous sample. Approximately 10 kg of FM was drawn from the container, mixed further, and then redistributed into the feeding containers in portions, ready for the experiment.

Kitchen waste consisted of equal amounts by weight of vegetable waste (kale, tomato, and cabbage), fruit waste (avocado, orange, and banana), and food waste (ugali, rice, beans, green gram, meat, arrowroot, sweet potato, and chapatti). The leftover fruits and vegetables were cut into small pieces of approximately 1 cm each to increase the surface area for BSFL exposure

Figure 1: *Containers with Kitchen Waste*

Feed Substrate Formulation

Three treatments, performed in triplicate, were prepared using FM, KW, and a mixture of FM and KW at a ratio of 1:1 according to the method by Achieng *et al.* (2023). The mixed substrates were thoroughly homogenized to minimize variation and replicate the pre-treatment mechanisms of shredding and grinding to increase surface area and mixing for thermal moderation used in BSFL systems (Gold *et al.,* 2020).

Effect of substrate performance on adult emergence and oviposition

Approximately 1 kg of each feed substrate (KW, FM & KW: FW=1:1) was placed into each feeding tray at once and left for them to feed until pupation. Five grams of five 5-day-old larvae were transferred into each treatment substrate. Feeding was monitored until the larvae attained pupal stage, identified by larval colour change from cream to black (Beyers *et al.*, 2023). The pupae were randomly selected, manually separated from frass, weighed and placed into pupation containers measuring 20 cm × 15 cm × 15 cm (Dzepe *et al.*, 2020). Each container held one kilogram of post-feeding larvae. The containers were then placed in three adult cages and monitored every two days for the number of emerging adults. Grooved flexible plastic tubes 3 cm wide in diameter were placed on top of the substrate attractants to serve as oviposition media. The weight of eggs oviposited was weighed and recorded until no more eggs were laid. Each experiment was replicated thrice for each substrate.

Figure 2: *Pupae ready for adult emergence*

Spatial, Adult Emergence and Colour Oviposition Preference for Adult BSF

Three cages prepared from net material of the same colour and quality and of dimensions 2.5m × 1.2m × 1.2 m, 2m × 1m× 1 m, and 1m × 1m× 1m were mounted. One kilogram of pupae reared from KW was placed into containers with pupation substrate and then placed in each cage. For this experiment, females needed to lay eggs around the same spot to facilitate egg collection, and therefore, an attractant was prepared by mixing 500 grams of maize germ with one litre of water and leaving it to rest until it produced a fermentation odour. The grooved flexible plastic tubes were placed on top of the substrate attractant for egg collection.

Adult emergence was measured by taking 50 grams of pupae from which adults had emerged and counting the number of empty pupal husks to determine emergence rates. The pupae were then returned to the cage and homogenized by hand. The process was repeated thrice for each cage. The weight of the eggs in each cage was recorded. Monitoring was done every two days, and the process continued until all adults had emerged. The experiment was replicated three times for each cage.

For colour oviposition preference, 1 kg of pupae was placed in a pupation container and then in a cage. The pupae had been reared from the KW feed substrate. These were monitored until the first flies appeared, after which similar plastic tubes of different colours (white, yellow, blue, and black) were placed in an attractant held in a container to collect eggs. The containers were of the same size and arranged in a line 15 cm apart with adequate light to allow BSF to orient towards their preferred colour while minimising bias from crowding. The egg weight from every grooved plastic tube was recorded every two days. The process was monitored until no more eggs were laid.

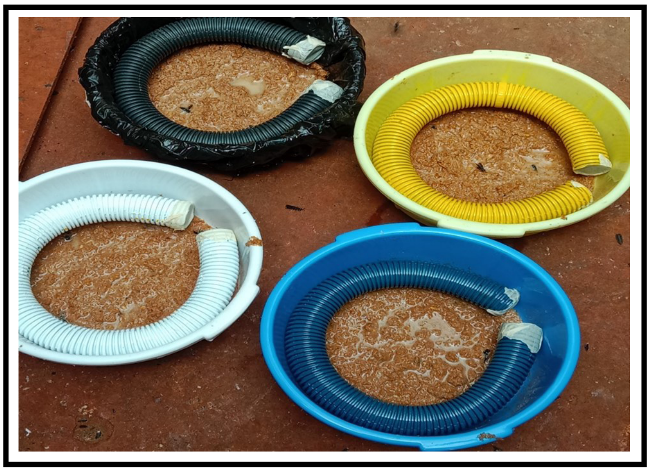

Figure 3: *Plastic pipes of different colours used to collect eggs*

RESULTS AND DISCUSSION

Feed Substrate Effect on BSF Oviposition

A significant difference was observed in the oviposition behaviour of the BSF across various feed substrates ($P < 0.05$), as illustrated in Table 1 below. Among the three substrates tested; KW, FM and KW: FM=1:1, FM: KW =1:1yielded the highest average oviposition weight, of 9.38 grams, with KW and FW measuring 4.65 g and 5.22 grams respectively. This highlights the efficacy of the kitchen waste and faecal matter combination in promoting BSF oviposition.

The study demonstrates that the type of feed substrate provided to BSF larvae significantly influenced the egg weight. While both KW and FM individually supported oviposition, the FM: KW (1:1) mixture resulted in the highest egg weight. The finding indicates that while all tested feed substrates sustained oviposition, mixed substrates resulted to more egg deposition, reflecting enhanced reproductive performance. Previous studies support this observation. Dortmans *et al.* (2017) noted that BSF reared on heterogeneous organic residues achieved better developmental and reproductive performance than those reared on homogeneous feed substrates. Similarly, Parodi *et al.* (2020) emphasized that mixtures of waste streams can provide a more favorable rearing environment than

	Type of Substrate	Mean	±	Std. Deviation
Egg weight (g)	Kitchen waste	5.22	±	3.63[a]
	Faecal matter	4.65	±	3.32[b]
	Kitchen waste and faecal matter	9.38	±	6.33[a]
Adult emergence rate (%)	Kitchen waste	74.99	±	2.49[a]
	Faecal matter	70.42	±	4.92[a]
	Kitchen waste and faecal matter	82.53	±	6.67[a]

Table 1: *Feed Substrate Effect on BSF Adult Emergence and Oviposition*

**Means followed by the same letter along a column for each parameter are not statistically different*

single wastes, enhancing both larval performance and adult productivity. Chia *et al.* (2023) also reported that mixed substrates yielded higher oviposition outputs and improved life-history traits, reinforcing the advantages of combined feed types.

Holmes *et al.* (2016) and Liu *et al.* (2020) observed that oviposition success and egg viability are strongly influenced by substrate type. Lalander *et al.* (2019) highlighted that combining waste streams under semi-controlled conditions improved BSF system efficiency and reproductive output. More recently, Frontiers in Sustainable Food Systems (2025) reported that substrate blending significantly increased egg production in semi-industrial rearing systems, confirming that this effect is not limited to laboratory-scale experiments. The present study contributes to the expanding body of knowledge demonstrating that the integration of substrates enhances BSF oviposition as evidenced by increased egg weight, and thereby holds potential to enhance the overall efficiency and sustainability of BSF-based organic waste management systems.

Feed Substrate Effect on BSF Adult Emergence

On the other hand, this study observed no significant ($P > 0.5$) differences in the emergence of BSF across the various rearing substrates; KW, FM, KW: FW=1:1 The percentage of adult emergence across these feed substrates, were 70.42%, 82.53% and 74.99% for KW, FM, KW: FW=1:1, respectively, as summarized in Table 1. Centre et al. (2022) reported that larval feed substrate had no influence on BSF adult emergence. This relative stability contrasts with the broader Diptera, where more variable responses have been documented. Similarly, Barragan-Fonseca *et al.* (2019) reported that adult emergence and larval hatching remained unaffected by variations in larval feeds, even as other traits such as development time and egg yield shifted. In contrast, Liu *et al.* (2024) demonstrated feed substrates affected all developmental stages in a BSF lifespan.

Colour Preference of Black Soldier Fly Oviposition Structure

For colour preference, the black pipe recorded the highest egg deposition (2.39 g), followed by blue (1.14 g) and white (0.64 g), with differences being statistically significant ($P < 0.05$) (Table 2). In contrast, the yellow pipe yielded the lowest oviposition (0.33 g), further highlighting the marked colour preferences exhibited by BSF during oviposition, as shown in table 2 below.

Pipe Colour	Weight (Mean) (g) ± SD
Yellow	0.33 ± 0.36[a]
White	0.64 ± 0.59[b]
Black	2.39 ± 1.73[c]
Blue	1.14 ± 0.82[d]

Table 2: *Mean Weight of the eggs (grams) of BSF and Colour Preference*

**Means followed by the same letter along a column are not statistically different.*

BSF rely on visual and thermal cues when selecting oviposition sites and colour serves as a key visual cue, helping females locate suitable substrates that signal appropriate microclimates for egg development. The higher preference for black colour could be as result of its resemblance to the natural habitats providing cues of shelter, moisture retention, and favourable temperature for egg and larval survival (Liu *et al*., 2022) These findings generally align with previous studies showing a preference for specific colours. For instance, preference for blue surfaces in BSF and other fly species, as reported by Romano *et al*. (2020) and Lamin *et al*., (2024). Additionally, Oonincx *et al*. (2016) identified that BSF are sensitive to blue and green light, which may explain colour preference. In another study, the blue-coloured platforms led to significantly more egg clutches and weights compared to the white platforms (Saxena *et al*., 2014). However, these results differ from studies on Drosophila spp., where dark-coloured backgrounds were avoided (Schnaitmann *et al*., 2020). These insights are valuable for enhancing BSF-rearing systems, particularly under artificial conditions.

Influence of Space on Adult Emergence and Oviposition of Black Soldier Fly

Comparing the adult emergence against the size of the cage, emergence was successful across all cage sizes with no significant variation (P>0.05) in emergence rates. The emergence rate in all three different cage sizes recorded close values ranging from 64.53% in the 1 × 1 m cage to 65.17% in the 2 × 1 m cage and 66.08% in the 2.5 × 1.2 m cage as summarised in Table 3. In contrast, egg weight was significantly affected by cage size ($p < 0.05$). The 1 × 1 m cage yielded the lowest oviposition output (4.53 g), the 2 × 1 m cage produced a higher weight (11.19 g), while the 2.5 × 1.2 m cage recorded the highest egg weight (16.38 g). These results (table 3) suggest that although adult emergence remained stable across cage sizes, larger cages created more favourable conditions for mating and oviposition, thereby enhancing egg production.

This research supports the view that rearing cages of 2.5 × 1.2 m significantly enhance oviposition of BSF. Studies conducted by Liu et al. (2022) and Isa & Hasan (2021) indicate that cages of dimensions 2.0 m × 4.0 m × 2.5 m promote more natural mating behaviours, leading to improved egg production. In contrast, smaller cages tend to restrict flight space, which can hinder mating success and reduce the efficiency of oviposition. Additionally, Julita *et al.* (2020) highlighted the critical role of adequate space in maximizing egg production efficiency, pointing out that the constraints imposed by smaller cages of 1 × 1 × 1 m may adversely affect the reproduction of BSF.

	Cage Size (m)	*Mean± Std. Deviation
Adult emerging rate (%)	1 ×1	64.53 ± 5.66[a]
	2 ×1	65.17 ± 5.39[a]
	2.5×1.2	66.08 ± 4.94[a]
Egg weight (g)	1 ×1	4.53 ± 1.03[a]
	2 ×1	11.19 ± 2.14[b]
	2.5×1.2	16.38 ± 3.92[c]

Table 3: *Cage size, Adult Emergence and Oviposition of Black Soldier Fly*

**Means followed by the same letter along a column for each parameter are not statistically different*

The findings from the study reveal that the size of the ovipositing space, particularly the dimensions of breeding cages, plays a crucial role in determining the reproductive success of BSF. The implications of these results are significant as they suggest that varying the sizes of breeding cages could lead to diverse responses in BSF reproduction. Therefore, for waste managers who are considering the BSF as an effective waste treatment solution, it is important to consider the influence of cage size on adult fly performance and reproductive outcomes. By enhancing cage dimensions, waste managers can improve overall breeding success and enhance the efficiency of BSF in waste processing.

Conclusion

This study demonstrated that BSF reproductive performance was influenced by both feed substrate, cage size, and oviposition site colour. The combination of KW and FM (1:1) produced the highest oviposition output, highlighting the advantage of complementary substrates in supporting egg production. While adult emergence rates remained relatively stable across different substrates and cage sizes, oviposition output was significantly enhanced in larger cages (2.5 × 1.2 m), emphasizing the importance of adequate space for oviposition. In terms of colour preference for oviposition structure, BSF females exhibited a marked preference for black structures, with the lowest deposition observed on yellow surfaces, underscoring the role of visual cues in ovipositing.

Our findings present a range of practical strategies to enhance the production of BSF, which can be employed to efficiently manage and recycle faecal matter, recovering valuable nutrient resources, thereby promoting citywide sanitation, significantly diminishing environmental pollution, and fostering sustainable economic growth within our communities.

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Conflict of Interest

The authors state that there are no conflicts of interest related to this publication.

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