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*Research article*

# Advancing circular economy principles through wild black soldier flies

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**Abstract:** Biowaste management poses a significant and widespread challenge. However, its consideration as a resource has led to the emergence of innovative and sustainable biowaste management techniques. One such promising solution is the use of black soldier flies (BSF) in biowaste treatment. This technique offers various advantages, such as the transformation of biowaste into versatile products that can be used in agriculture, horticulture, aquaculture, animal husbandry, pharmaceuticals and energy production. Despite significant research on different aspects of the BSF biowaste treatment system, none have explored the application of circular economy principles in low-income settings using naturally occurring BSF, i.e., free-range BSF. This article addresses the gap utilizing a mixed-method approach through a case study to achieve two objectives: the localization of the circular economy through co-production with a community group and the viable production of black soldier fly larvae (BSFL) and compost to meet the community's needs. Through collaboration, a successful circular economy was established as biowaste was transformed into products and safely reintroduced into the local biosphere. Performance indices used included BSFL nutritional composition, harvest rates and heavy metal absence.

Through community involvement, circular economy principles were effectively implemented to redirect a retail market's fruit and vegetable waste from the landfill. The free-range open system produced 19.15 kg of BSFL, with 44.34% protein content, 20.6% crude fat and zero heavy metals. These outcomes align with existing research, indicating that a community-led open BSFL system can generate valuable products while fostering circular economy principles with minimal financial,

technological, energy and water resources.

**Keywords:** black soldier fly; free-range BSF; circular economy; biotechnology; bioeconomy; biowaste; co-production; community-based; Tanzania

## 1. Introduction

Despite the emergence of advanced technologies, solid waste management remains a global challenge. While 37% of waste is landfilled globally, the percentage differs significantly by GDP. High-income countries landfill 28%, upper-middle-income countries landfill 54% and low-income countries openly dump and landfill 93% of their waste [1]. These contrasting values highlight the importance of economies in waste management and suggest that a solution will need to be more than technological [2]. As much as 44–80% of globally generated solid waste is biodegradable [3,4] and can be diverted and integrated into a sustainable non-linear consumption and production model. Biowaste is biodegradable matter consisting of food waste from households and institutions, market waste and food and wood processing wastes [5]. Several technologies provide biowaste diversion and integration opportunities. Biological technologies, like composting, vermicomposting, black soldier fly (BSF) treatment, fermentation and anaerobic digestion, are feasible organic waste management technologies for low-income locations due to their technological simplicity and adaptability. However, urban and peri-urban space constraints limit the applicability of composting [6,7] and vermicomposting. Compared to other biological waste treatments, the BSF method produces maximum mass reduction with the least spatial requirement [8]. This is an important consideration in highly populated urban settlements [6]. Other considerations include an emphasis on social and environmental sustainability in addition to technology [9,10]. The failure to incorporate sustainability considerations has resulted in technologies disassociated from the social, cultural and environmental realities of the demography they were designed to serve [2,11,12]. To better incorporate these considerations, this study tailored the principles of the circular economy (CE)–a sustainability concept–to satisfy the resource needs of a low-income community using naturally occurring BSF, i.e., free-range BSF.

BSF technology is well researched, but there is a considerable knowledge gap in open BSF technology, its outputs, its benefits to low-income communities, and its contribution to the circular economy (CE). This study contributes to filling the gap by providing data on free-range BSFL produced from an open system designed and operated using CE principles.

### *1.1. Black soldier fly biowaste treatment method*

The BSF, *Hermetia illucens* (L., 1758) (Diptera: Stratiomyidae), is used in a biological treatment method that is environmentally beneficial [13,14], non-cost-prohibitive [15,16], located in most parts of the world [17] and suitable for low- and middle-income countries [16,18]. BSF waste treatment method is an emerging biowaste management technology used to valorize biowaste into frass biofertilizer while generating larvae for animal or human feed [19]. BSF frass is the residue and byproduct of BSF larvae degradation of biowaste. It comprises leftover decomposed biowaste, BSFL molt and feces [20]. Frass as a soil amendment is becoming more widely accepted because it is rich in

essential nutrients and can be used as an organic fertilizer [21]. Prepupal BSFL, consists of 42% crude protein and 29% fat at the last larval phase and is rich in vitamins, micronutrients and saturated and polyunsaturated fatty acids, making it an attractive enterprise for animal feed production [15,22,23].

BSF biowaste processing systems are based on the BSF lifecycle, from eggs to adult flies, with biowaste treatment occurring in the larval phase. The system can be run in different configurations [18,24], including the popular enclosed systems where the flies are bred in captivity and used to treat biowaste [8,15,25]. This adult BSF rearing and egg production system [24] is referred to as a closed system in this article. Open systems, alternatively, allow wild BSF to breed and bioconvert waste while unconfined [17]. This system is based on natural egg production, i.e., natural oviposition, where the adult BSF remains unconfined, similar to free-range animal husbandry, hence the adoption of the term.

BSF are a robust and "extremely resistant species capable of dealing with demanding environmental conditions, such as drought, food shortage or oxygen deficiency" [26]. Therefore, BSF biowaste treatment systems are easily adaptable to location requirements and can be designed as simple or complex. Studies have reported that the egg production, biomass conversion and development rates of BSFL are influenced by various factors like climatic conditions, lightening [8], aeration, temperature regulation, feeding rates and feedstock type [24,27], biowaste quality [16], nutritional composition [28], moisture content and particle size [8]. Therefore, unlike open BSF systems, closed systems must maintain environmental conditions by using additional resources like energy to keep the process running. However, this factor makes closed systems more efficient since BSFL production is predictable. This is not the case with open systems which are exposed to and influenced by changing environmental conditions [24].

Open biowaste treatment systems farm wild BSF in their natural habitat, i.e., free-range. The setup consists of a bioreactor which is filled with locally sourced fruit and vegetable waste that attract female BSF and promote oviposition [17]. The larvae that hatch from the eggs are capable of digesting and converting the biowaste into useful byproducts in the bioreactor with minimal technological or human intervention. This makes the solution feasible for low-income communities in tropical climates where BSF are naturally occurring. In these communities, micro-livestock and micro-farming are prevalent, which makes the BSF byproducts valuable as animal feed and biofertilizer. Open BSF systems are simple to construct, operate and maintain and they require low capital investment [16]. Their production ratios vary depending on the infrastructure used, which ranges from plastic buckets to wooden or concrete structures. The simplicity and diversity of open BSF treatment systems offers a practical solution for communities with significant biowaste fractions and restricted budgets. This technology's versatility and ease make it an excellent choice for locations like Belo Horizonte, Brazil, where biowaste accounts for 61% of the waste [29]. Other regions that could benefit from this simplified technology include Nigeria, which produces 60–80% [3,4], Ghana, which generates 65–73% [11] and Tanzania, where 35–80% of the waste fraction is biowaste [28,30]. Kenya produces 59–74% [20], while in La Paz, Bolivia, the ratio is 47% [31]. Bangladesh and Pakistan also face high biowaste levels, accounting for over 65% of their waste fraction [32]. In order to develop a sustainable model, CE principles and business models were used to determine BSF byproduct production and consumption rates relevant to a high biowaste-generating community.

### *1.2. Circular economy*

There is growing interest in moving from linear to circular material flows [33], evidenced by the notable increase in the adoption of circular economy principles in the past decade [34,35]. The circular economy defines environmentally friendly economic systems based on the cradle-to-cradle lifecycle of products, components and materials. The concept of the circular economy is centered around reducing the consumption of new resources and minimizing waste generation. This is achieved by enabling the circulation of resources within both technological and biological systems [21]. The resulting benefits from the circular economy have been new business opportunities, job creation, reduced greenhouse gas emissions and the avoidance of import dependency, waste and resource depletion [34]. The circular economy has been identified as an evolving fluid concept that links concepts like cradle-to-cradle design, zero waste and cleaner production [35]. The circular economy is highly relevant in biowaste management because it highlights the significance of recycling materials and energy by transforming them into valuable resources that benefit others [21]. Therefore, biowaste treatment using free-range wild BSF can be considered an innovative circular economy approach [21].

Circular economy origins have been traced from systems ecology in the 1960s–70s [34] and industrial ecology and industrial symbiosis in the 1990s [21], with its recent advocates including policy-makers and practitioners like the Ellen MacArthur Foundation [35]. Although beneficial in many aspects, the circular economy has been criticized for promoting weak sustainability by perpetuating the belief in natural capital regeneration through technology [34]. Additionally, circular economy studies have been high-income country-oriented, making its application in low- and middle-income countries challenging [33,36]. Biowaste management through circular economy strategies, principles and business models is scarce, with the majority focused on high-income countries and national perspectives [21]. The drivers for adopting a circular economy differ in the context of high- versus middle- and low-income countries. While resource security and environmental protection are prioritized in high-income countries, middle- and low-income countries will be more inclined to favor waste valorization for job creation and poverty reduction [36]. Middle- and low-income countries also inherently practice more circularity than high-income countries [37]. Highlighting the circular economy knowledge gap for developing countries, Wright et al. questioned if its adoption will enhance economic growth and sustainable development in these locations [36]. Another major flaw in the current approach to the circular economy is its emphasis on promoting environmental benefits without adequately incorporating social factors into economic activities [34,38–40]. Despite focusing on job creation as a key social indicator, the circular economy overlooks important factors such as participation, social inclusion, poverty and food security [39]. Hence, studies by Velenturf et al. [34] and Suárez-Eiroa et al. [35] have proposed principles that integrate sustainable development-based societal considerations in the circular economy. This article contributes to the literature by implementing modified circular economy principles in an empirical study. CE principles were "domesticated," making them contextually relevant [36].

### *1.3. Theoretical framework*

Socio-economic and management considerations are lacking in waste management case studies [5] and their integration in the decision-making process is critical in developing countries [41]. This study attempts to incorporate these elements using CE and co-production in a simple community-based

biowaste treatment system.

Co-production happens when people intentionally contribute time and effort to produce services that were once solely managed by professionals [42] and it improves research methodology by expanding how knowledge is produced [43]. This approach was vital because lower-income communities require unconventional solutions that prioritize community involvement in the decision-making process [44]. Elinor Ostrom initiated co-production analysis in the provision of public service [43], but it has since been widely adopted. Co-production promotes social inclusion and citizen engagement because the service users are engaged in systematic dialogues that ensure a horizontal form of knowledge production [43,45]. Therefore, conventional objectives in biowaste technology, like maximum waste reduction and maximum BSFL yield, may not be desired by the users and become irrelevant, as seen in this case study. Community participation aids co-production because it leads to the identification of community problems [6] and not just the individual. Community participation is defined as "an active process by which the community influences the direction and execution of a development project to enhance their well-being in terms of income, personal growth, self-reliance, or other values they cherish" [6]. Community participation facilitates the autonomous use of infrastructure by the community, which is a requirement of this study with priority given to "community residents who rely on themselves to improve the conditions in their community" [6]. The adoption of co-production and use of BSF technology were necessitated by the requirements for collaboration and waste diversion. This strategy produced forecasted outputs from the research participants and literature. Indicators from the CE were used to quantify and qualify the outputs. Figure 1 illustrates the overall framework, showing the relationships between the concepts and outputs.

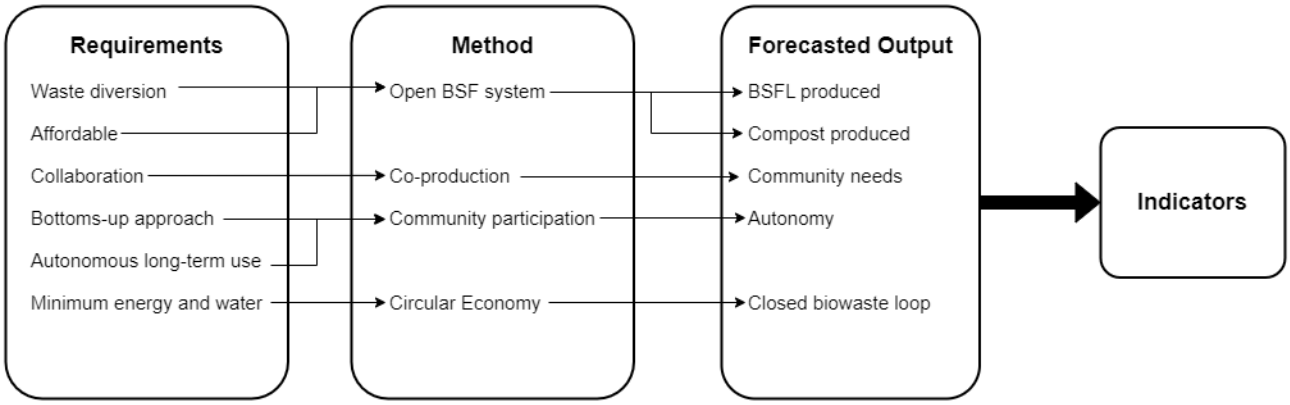



**Figure 1.** The study framework.

The study broadens the application of the CE by outlining the previously unexplored approach of using free-range BSF to solve an environmental challenge while meeting the needs of a low-income community. In using free-range BSFL, co-production techniques, thorough reviews of existing literature and qualitative research methods such as focus group discussions and direct observations, this study provides valuable insights into how a community-driven CE can work.

## 2. Materials and methods

### *2.1. Study location: Kipunguni, Dar es Salaam*

The empirical study was conducted in partnership with AMREF Health in Africa Tanzania and the BSF system constructed on property owned by *Sauti ya Jamii Kipunguni* (Voice of the Community Kipunguni), the community partner. Members of the community group co-created and managed the entire process. The findings presented in this article ran between September 2022 and July 2023.

Kipunguni in Ilala municipality, Dar es Salaam, Tanzania, is a peri-urban community located 6.91844° S and 39.17309° E. The location is 19 km southwest of Dar es Salaam city center and 14 km northeast of Pugu Kinyamwezi landfill, Figure 2. A baseline study conducted by AMREF Health in 2018 of four municipalities in Dar es Salaam, including Ilala, places the average solid waste generation per capita lower than the region at 0.29kg/capita [46]. Global waste generation is recorded as 0.74 kg/head per day [1], and Sub-Saharan countries like Kenya generate 0.65 kg/capita per day [20]. Kitchen and yard waste constituted 61% of waste fractions, of which 49% was food waste and 12% was yard waste [46]. The high biowaste fraction confirms the study location as an optimal site for BSF biotechnology.




**Figure 2.** The Study Location; BSF bioreactor, Pugu Landfill, and Dar es Salaam City Centre. (Source: Trong R. Kipunguni Case Study Map. Calgary: University of Calgary Spatial and Numeric Data Services (SANDS),2023). Base Layer Credits: Esri, FAO, NOAA, USGS, NASA, NGA, HERE, Garmin, Foursquare, METI/NASA.

#### 2.1.1. Ethics approval of research

This project was reviewed and approved (REB# 21-15-33) by the University of Calgary's Conjoint Faculties Research Ethics Board (CFREB), which operates under the current version of the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* (TCPS) on February 3, 2022. Ethical clearance was also granted by National Institute for Medical Research on June 7, 2022 and by the Tanzanian Commission for Science and Technology (COSTECH) on August 15, 2022. The research participants provided written informed consent.

### *2.2. Case study design*

The case study was part of an extensive study investigating the independent community management of small- to medium-sized BSF operations replicable in urban or peri-urban low-income communities [40]. Two BSF pilot studies were conducted, and their learnings were incorporated into the case study.

The study was designed to collect and analyze CE related qualitative data and BSF related quantitative data.

In consultation with the community group (*Sauti ya Jamii Kipunguni*), the following requirements for BSF-related data were determined. These needs were based on a review of literature, pilot study findings and focus group discussions.

1) A simple BSF system
2) Minimal machination
3) Training and mentoring of all community members
4) Byproducts that satisfied their micro-livestock and agriculture needs
5) Economic viability

Therefore, the indicators monitored during the study included work hours, energy input, number of community members trained and involved in the project, waste collection volume, BSFL and compost production rates, BSFL nutritional composition and byproduct use by the group and community. Table 1 provides the CE related indicators.

### *2.3. Circular economy principles and their application*

The BSF system was customized to fit the area's specific environmental factors while meeting the local population's social and cultural needs. Economic considerations recognized the financial limitations of the community [44] and was integrated in the study by using the open BSF system. The operational plan, co-designed with the community partner, was developed and refined as the biowaste resource loops were identified and closed. The operational objectives included achieving maximum waste reduction, no by-product toxicity, minimal energy and water inputs and minor maintenance. Figure 3 illustrates the operational plan used in the study. The green arrows represent processes that aided in the closure of the resource loop, while the yellow arrows, although not studied, have the potential to contribute to the circular economy. The red arrows indicate processes that do not facilitate the closing of the resource loop.

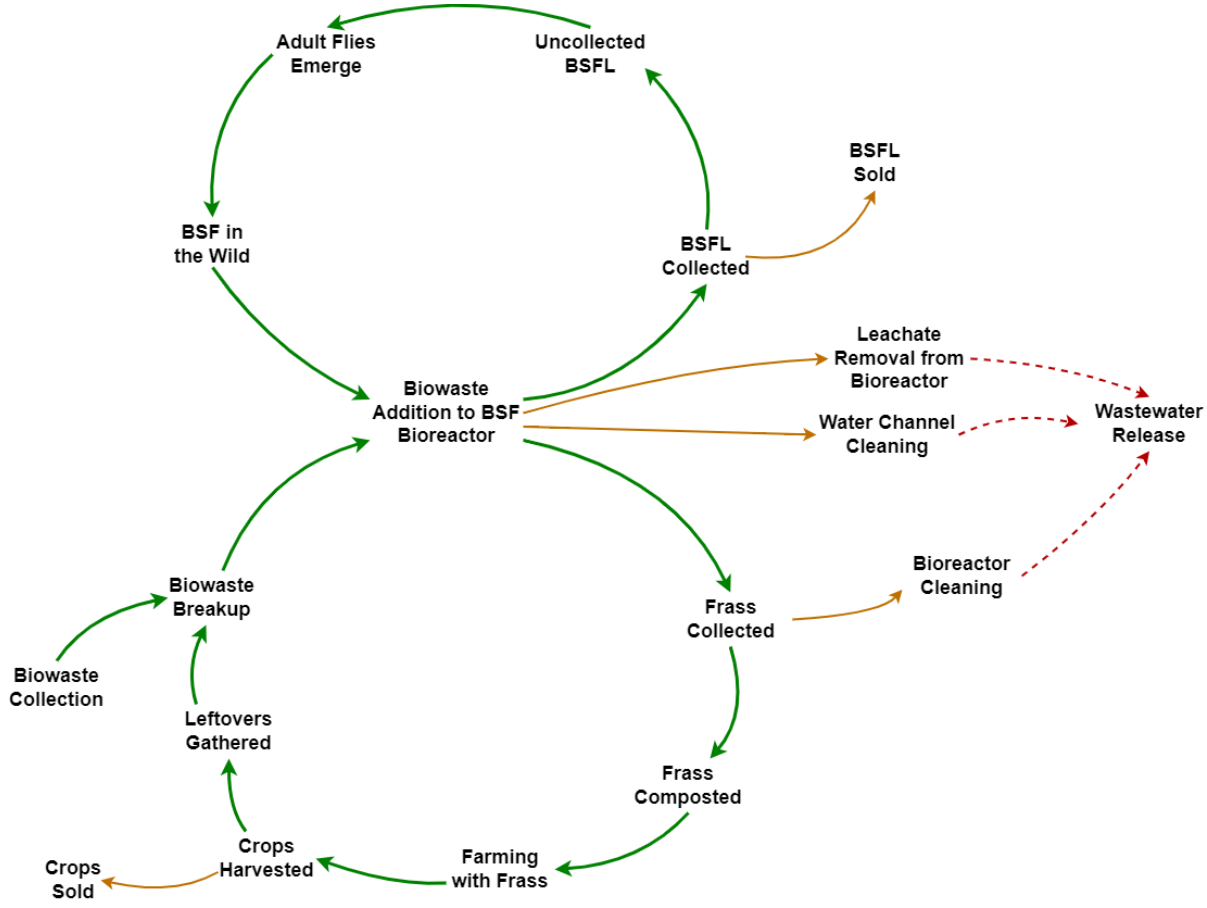



**Figure 3.** Circular BSF Operations. Red Arrows denote the operations that did not close the resource loop.

The CE indicators listed in Table 1 were compiled from relevant literature [21,33–35,39,47–49], including the social circular economy model (SCE). The SCE, a modified CE, integrates environmental principles with the societal goal of social enterprises [50]. The indicators, beginning with resource recovery, consider waste a resource. This is an increasingly common practice [51,52] and can be attributed to the CE. Resource recovery, which is represented as a biological materials cycle by the Ellen MacArthur Foundation [33], recovers biowaste that would otherwise be considered not valuable. Its importance cannot be overstated and it has been defined as the "backbone of a circular economy" [52]. Resource recovery was tracked by measuring the biowaste and the byproducts generated using the open system. An emphasis on circular inputs diminishes the importance of energy and water in locations where these resources are scarce. Job creation and labor required are always important parameters. SCE highlights the importance of a community champion which is termed project champion or project lead in the case study. The champion works closely with the researchers and leverages their close connections with their community to transfer knowledge, resolve conflicts and identify opportunities, thus ensuring the project's longevity. Integrating the community at large also contributes to extending the lifespan of the project. Finally, the complexity of biowaste management in low-income communities demands innovation which can be discovered in comparing the research teams research-based design and the co-produced design implemented in the case study [40].

**Table 1.** CE related indicators.

| Indicator | Reference | Relevance | Measurement |
|---|---|---|---|
| Resource recovery | CE, [33] | Closed resource loop. | Quantity of biowaste collected. Quantity of BSFL and frass harvested. |
| Circular inputs | CE | Energy and water conservation. | Energy use. Transportation. |
| Job creation | CE, [39] | Economic benefits. | Employees. |
| Labor required | SCE, [39] | Social benefit. | Work hours. |
| Community (project) champion | SCE | Knowledge transfer to participants. | Project lead. |
| Community integration | [38] | Project sustainability (longevity). | Quantity of BSFL sold and frass utilized. |
| Innovation | [38] | Open dump eradication, food security. | Difference between pre-designed and co-designed project. |

### *2.4. The black soldier fly bioreactor*

The open BSF bioreactor used in the case study is a 4.96 x 2.93 x 0.73 m, Figure 4 (A), concrete enclosure with corrugated roofing that is opened one sheet at a time, from left to right. The metal structure supporting the roofing sheets is covered with 25 mm chicken wire mesh to prevent pests and rodents like lizards, geckos, birds, rats, etc. from entering the bin. Additionally, a 20 cm wide and 17 cm deep water channel was constructed as part of the bioreactor to keep ants and lizards from reaching the substrate and BSFL. All other insects small enough to get through the barriers, including BSF, could access the chopped-up biowaste deposited in the bioreactor and build a colony. However, the system was designed and constructed based on two fundamental premises.

- Female BSF are attracted to and prefer ovipositing (laying eggs) at sites with the sweet smell of decomposing fruit [15]
- BSF will outcompete other species over time, resulting in a dominant BSF colony [17]

In the case study, wild female BSF were lured to the bioreactor with the decomposing biowaste placed in it. The flies enter the bioreactor through the chicken wire mesh and lay eggs, which later hatch into larvae. These larvae then feed on the biowaste until they mature into pre-pupae and self-migrate to the harvesting section.

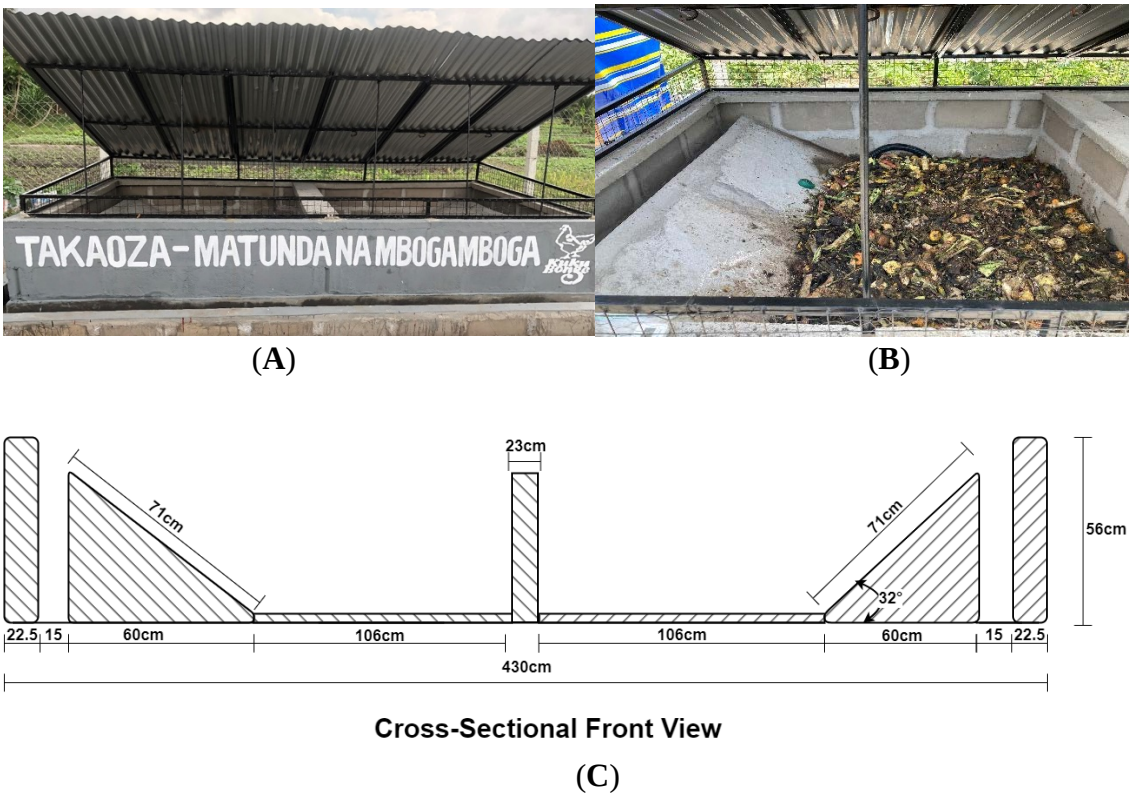



**Figure 4.** Open system bioreactor (A) Cross-sectional illustration of the bioreactor (B) Bioreactor (C) Bioreactor section with biowaste contained in it (Source: Authors).

The bioreactor is made up of two replica bins. Each bin comprises a bioconversion section which leads to a harvesting section via a 32-degree ramp; see Figure 4 (C). The bioconversion section is a mass-rearing compartment that contains biowaste, eggs laid by the female BSF and masses (clusters) of BSFL. The existence of two bins allowed for rotational use.

### 2.4.1. Byproduct: black soldier fly larvae

BSFL quantity measurements (weights) were only taken from the harvesting section and drying unit, i.e., larvae feeding on biowaste in the bioreactor were ignored. To measure the larvae, the harvesting section was emptied using a plastic scoop and larvae were sorted by species. Measurement was limited to the harvesting section to reduce interference to the system. This operational plan was tailored to suit the community group who were scheduled to take over the project.

Furthermore, nutritional and mineral analyses of the BSFL were conducted. The IITA laboratory in Dar es Salaam tested 250 g samples of BSFL. The samples were analyzed for crude protein, ash, crude fat, nitrogen content and minerals, including heavy metals. At the lab, samples were weighed, and moisture content was determined before oven-drying the samples at 103°C for 24 hours. The weights and moisture content were recorded and utilized in determining the dry matter. Ash was determined by heating the samples in a Nabertherm furnace from 30°C till it reached 550°C. Crude fat was measured using Fross Soxtec 2043 for oil extraction, and protein content was calculated based on the nitrogen content using Equation 1.

$$\text{Percentage protein (\%)} = \frac{(T - B) \times M \times 14.007 \times 100 \times 6.25\text{MCF}}{W} \quad (1)$$

Where

- $T$ = Volume of the standard hydrochloric acid used in the sample titration.
- $B$ = Volume of the standard hydrochloric acid used in the blank titration.
- $M$ = Molarity of the acid in four decimal places.
- $W$ = mass of the sample used in the determination in milligrams.
- 6.25 = factor used to convert percent N to percent crude protein. Most proteins contain 16% N, so the conversion factor is 6.25 (100/16 = 6.25).

2.4.2. Byproduct: frass biofertilizer

A drying unit was constructed in addition to the bioreactor for curing BSF frass and harvesting BSFL trapped in the frass. The unit was made of corrugated metal, metal rods, wood, and wire mesh. The drying process begins by harvesting moist frass from the bioreactor and placing it on a wire mesh in the drying unit. The frass is exposed to sunlight and left to dry for three weeks, resulting in its conversion to compost. Sun exposure prompts the photophobic BSFL to move to the bottom of the frass and drop into a harvesting container located under the screen. The community group used the harvested BSFL and compost. They also sold BSFL to the community on demand.

*2.5. Black soldier fly open system operations*

The BSF bioreactor was constructed on property owned by *Sauti ya Jamii Kipunguni* community group, adjacent to their offices, making the aesthetic and odor management of the bioreactor critical. Animal-based protein was excluded from the system to minimize odor, substrate contamination, and health risks. Additionally, the biowaste in the bioreactor was manually aerated every other day to prevent unpleasant smells. Manual aeration involved using a shovel to turn the biowaste, allowing air to circulate and prevent anaerobic conditions.

Biowaste added to the bioreactor included tomatoes, peppers, carrots, mangoes, banana peels, oranges, watermelon and pineapple rinds, vegetables including spinach, cucumbers, avocado, jackfruit (*Artocarpus heterophyllus*) and Tanzanian pea bean peels. A flatbed tricycle (Toyo) was used to move biowaste to the study site. Biowaste was sourced at night when the retailers were ready to dispose of decomposing fruits and vegetables. The waste was left in the tricycle overnight and added to the bin the next morning. Material flows in and out of the bioreactor and drying unit were tracked by measuring biowaste added and the BSFL, frass and leachate removed, Figure 3. Nutrients contained in the leachate were not reintroduced into the resource loop, resulting in sub-optimal resource recovery. The harvesting of BSFL was based on the demand of the community group and customers. Anything that was not harvested was left undisturbed in the harvesting section until needed or metamorphosed into flies. Therefore, the data presented in this article represents the community's demand for BSF byproducts, as well as their availability to collect and process waste. It does not reflect the optimal input and outputs of the open system.

The free-range BSF process ran over a 6-week cycle that included waste acquisition, natural oviposition, bioconversion, BSFL and frass harvesting. Curing the frass required an additional three weeks in the drying unit. Other day-to-day operations included cleaning the water channel around the

bioreactor.

## 3. Results

### *3.1. Closing the CE gap at study location*

The study identified the resource gap in the community as the disposal of fruit and vegetable waste by retailers to the landfill. An intervention was developed in collaboration with the community group resulting in a localized closed loop model represented in Figure 5 below.

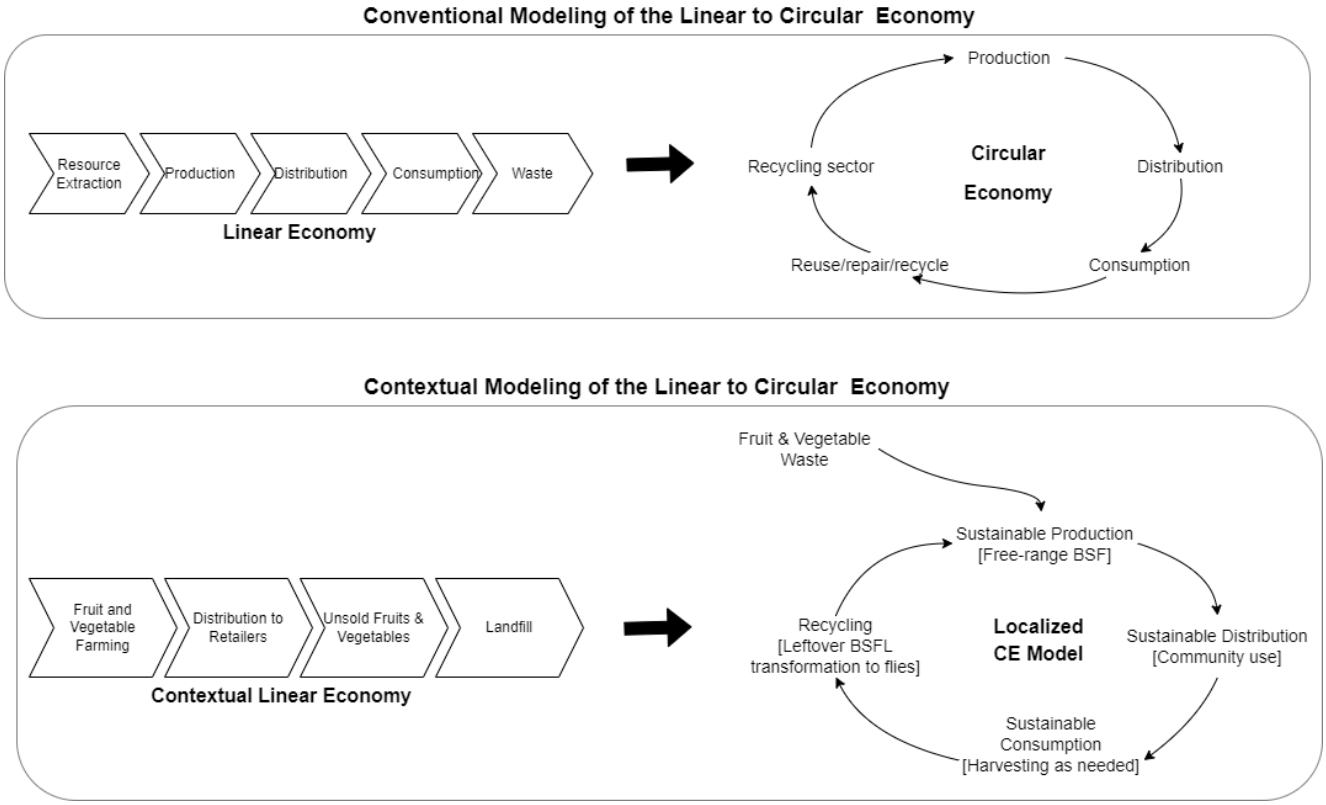



**Figure 5.** Localized circular economy closed loop model in comparison to the convention. (Source: Authors, [53]).

Home-to-home collection yielded 81 kg of biowaste over 11 days, while collection from a retail market 3km northeast of the study site resulted in 80 kg of biowaste in a day. The CE gap was distinguishable in the difference in biowaste availability. The households in the area practiced circularity by feeding biowaste directly to their livestock, a method discussed by Lohri et al. [5]. Biowaste collection in this study was therefore switched to the retail fruit and vegetable market.

Two tons (2576 kg) of waste were collected and treated using the BSF open system bioreactor, producing 19.15 kg of BSFL (wet weight) and 572 kg of frass (wet weight) over 148 days. The frass was cured in the drying unit to produce 201 kg of compost (dry weight) and 62.5 kg of discarded cured frass (dry weight) because it comprised of mango seeds and large pieces of decomposed biowaste. Figure 6 illustrates the decomposition from biowaste to frass and compost.

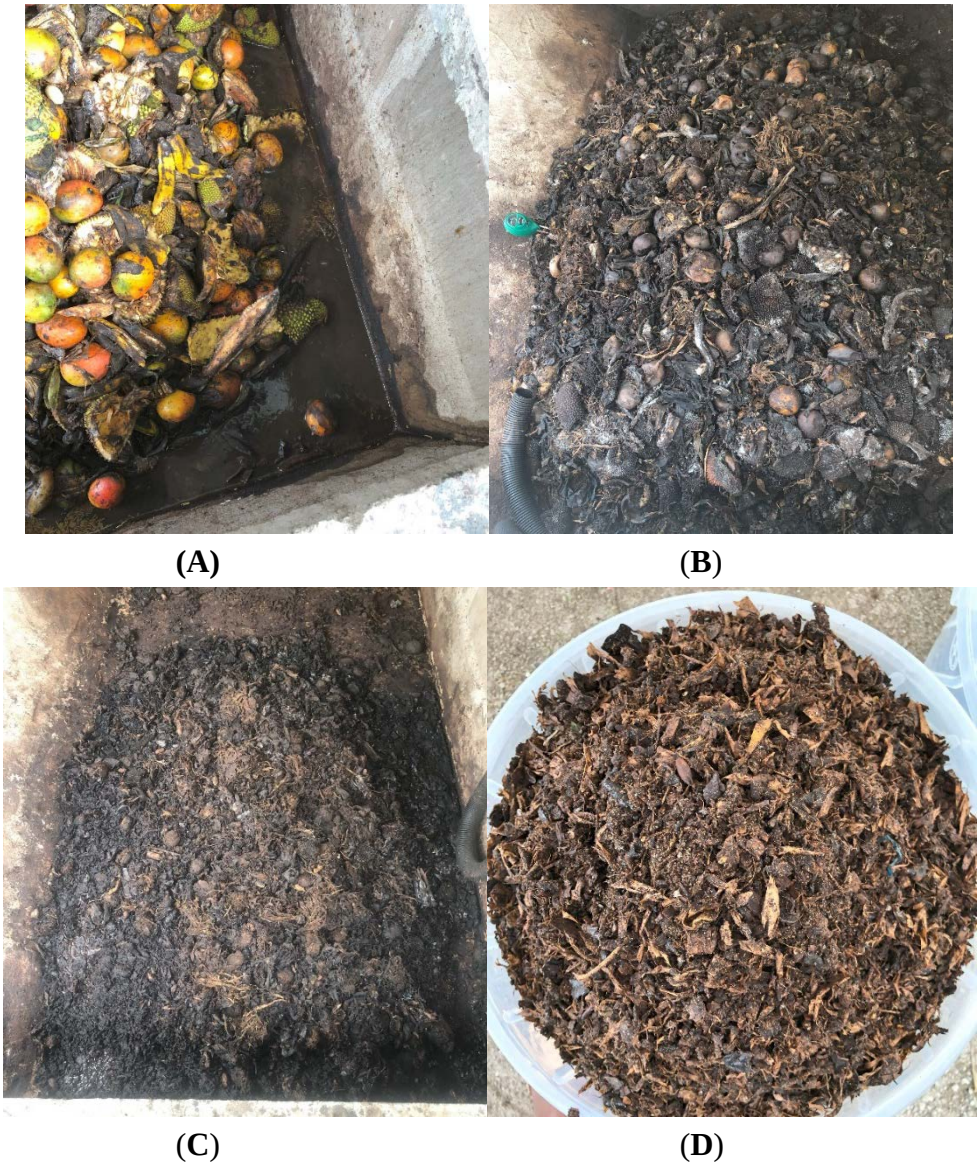



**Figure 6.** Biowaste to compost transformation (A) Biowaste at day 2 (B) Biowaste at day 16 (C) Frass/biowaste at day 35 (D) Filtered compost (Source: Authors).

Figure 7 represents the distribution of waste collected (based on the community group's availability), BSFL harvested (based on the group and customer demand) and compost generated (based on the technology and operation plan). The values are lower than the literature, i.e., 10% versus 0.74% BSFL to biowaste ratio and 30% versus 11% compost to biowaste collected [54,55]. However, these reference systems used captive BSF and not free-range BSF. Results from a free-range BSF study in Kenya [17], a neighboring country, correlate with the results of this study. Over a 6-month period, the Kenyan study harvested 17.6 kg with maize substrate, 13.2 kg with vegetables, 10.1 kg with *omena* (*Rastrineobola argentea*) and 5 kg with animal manure. The fruits and vegetables used in this study produce more BSFL than the study with maize.

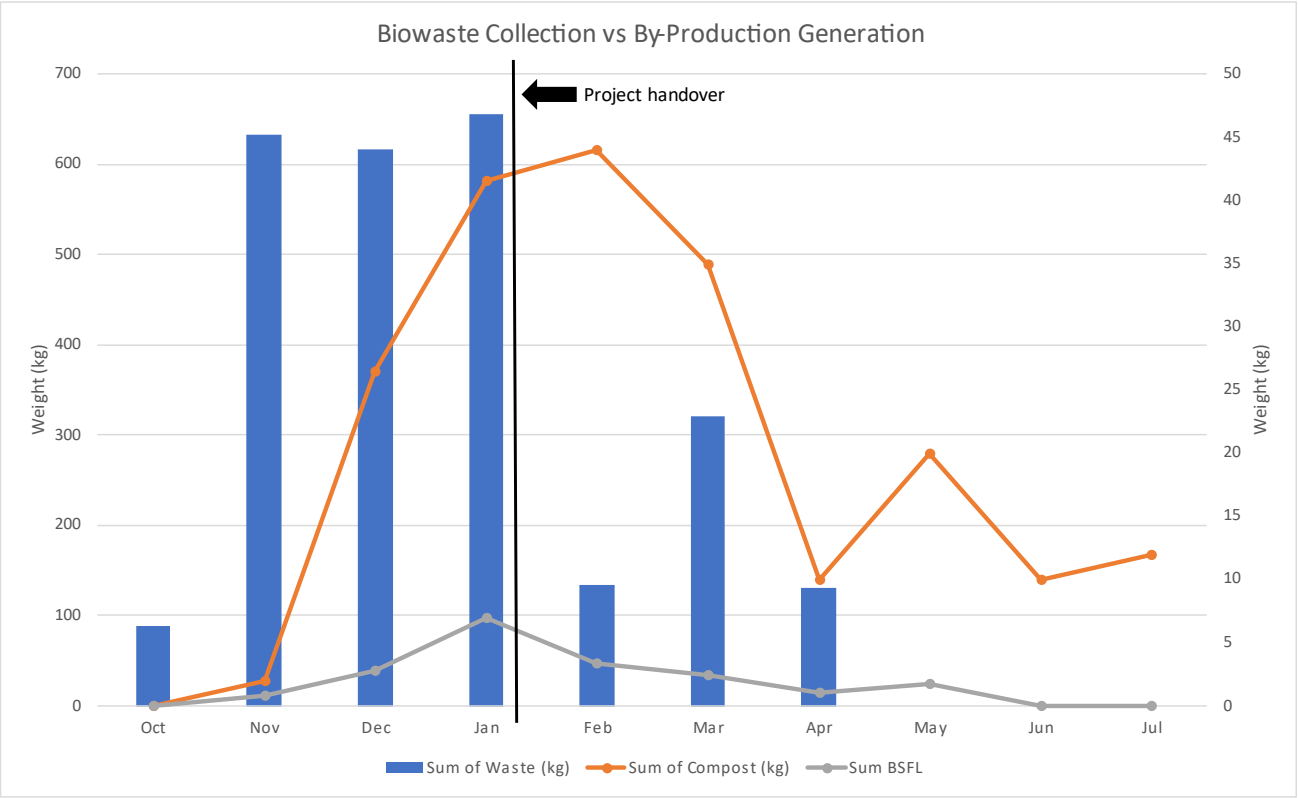



**Figure 7.** Localized circular economy and free-range BSF system output

The dip in biowaste collection occurred after the project handover to the community at the end of January. Handover was included in the study to identify autonomy. Additionally, heavy rains in January and February led to flooding of the bioreactor and raised the water table. This resulted in a decrease in the populations of BSF and BSFL. A free-range BSF experiment in Burkina Faso confirmed low BSFL production in rainy seasons [56].

The rest of this section is organized according to Table 1's CE indicators, which are resource recovery, circular inputs, job creation, labor requirements, community involvement and innovation.

### *3.2. Resource recovery and circular inputs*

In Kipunguni, Dar es Salaam, there is competition for dry biowaste like potato peels which are fed to livestock. The retailers and waste collectors perceive high moisture content biowaste like tomatoes and mangoes as a burden. Therefore, these stakeholders accepted the free-range BSF solution. However, larvae specie and leachate management were significant challenges because of this approach. The common house fly larvae (*Musca domestica*) was the first insect observed in the bioreactor and the species quickly became pervasive. It remained the only species in the substrate until day 10, when BSF was spotted on the substrate. On the same day, drone fly larvae (*Eristalis tenax*) were sighted in the bioreactor. These three species, pictured in Figure 8, were the only insects observed in the bioreactor throughout the study.




**Figure 8.** Bioreactor insects (from the bottom and left) - drone fly larvae, house fly larvae and black soldier fly prepupae.

By day 17, 18 g of pre-pupae BSFL migrated to the harvesting section. The average pre-pupae weight during the study was 155 mg. No drone fly larvae were observed or harvested by day 121 and this remained the situation until day 158. Table 2 provides the study measurements.

**Table 2.** Black soldier fly larvae and drone fly with housefly distribution.

| Day | BSFL (g) | Drone fly + House fly (g) |
|---|---|---|
| 17 | 18 | - |
| 21 | 75 | - |
| 37 | 902 | 250 |
| 68 | 2574 | 1128 |
| 99 | 6539 | 813 |
| 127 | 5561 | 433 |
| 158 | 1250 | 0 |
| 188 | 500 | 50 |
| 190 | 2622 | 0 |

In terms of BSFL nutritional composition, a community-need related indicator, the average protein content of the wild BSF in the case study was 44.51%, with an average nitrogen content of 7.12%. The crude fat of the wild BSFL was 17.3%. Table 3 provides a breakdown of the nutritional and mineral test results of samples collected on day 50 (sample 1) and day 142 (sample 2). Heavy metals like mercury, cadmium, arsenic and lead were undetected on day 134 (sample 3).

**Table 3.** Nutritional and mineral content of wild BSFL in study.

| Parameter | BSFL Sample 1 (mass %) | BSFL Sample 2 (mass %) | BSFL Sample 3 (mass %) |
|---|---|---|---|
| Crude protein | 44.34 +/- 0.220 | 44.68 +/- 0.133 | 58.4 |
| Nitrogen content (dw) | 7.09 +/- 0.035 | 7.15 +/- 0.021 | - |
| Crude fat | - | 17.30 +/- 0.027 | 16.1 |
| Mercury | - | - | ND* |
| Cadmium | - | - | ND* |
| Arsenic | - | - | ND*(<0.0001 DL**) |
| Lead | - | - | ND* (<0.0001 DL**) |
| Tin | - | - | 0.0011 (<0.0002 DL**) |
| Copper | - | - | 0.01 (<0.0001 DL**) |
| Manganese | - | - | 0.0569 (<0.0004 DL**) |
| Zinc | - | - | 0.0013 (<0.0001 DL**) |

*ND-None detected DL-Detection Limit.

Circular input, a CE indicator, addressed a community-need related indicator, minimal machination. Both indicators were measured by the energy input into the open system after construction of the bioreactor and drying unit. Energy input was zero, but fossil fuel was required to transport biowaste from the market to the bioreactor.

### *3.3. Job creation and labor required*

No jobs were created, but all members of the community group participated in the BSF operations. The group rejected the idea of hiring help. Work hours for the open BSF bioreactor varied depending on the bioconversion phase, and waste collection made the largest contribution with 8 hours averaged by for people each, totaling 32 hours per cycle, i.e., over 6 weeks. Figure 9 shows the average distribution by task per cycle. The total work hours on the project averaged 575 hours, which was more than the community group was able to maintain, as evidenced by the drop in waste collection after the project handover.

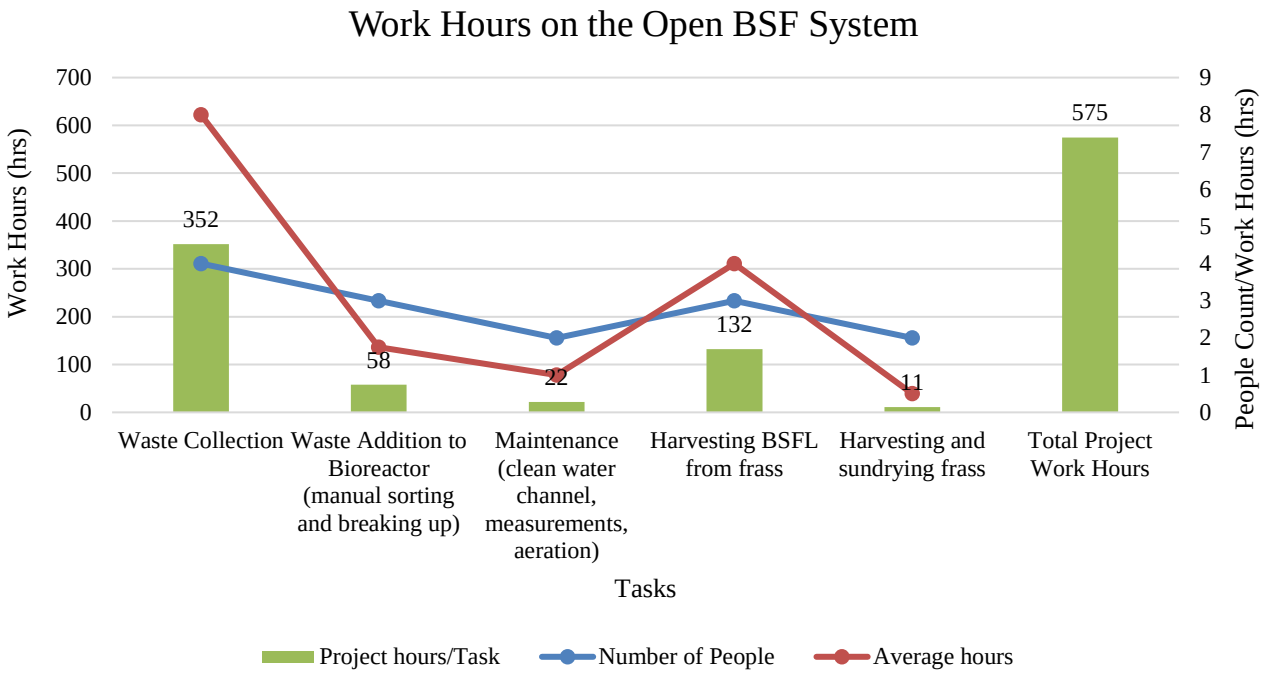



**Figure 9.** Works hours tracked as an indicator.

### *3.4. Community champion, community involvement and innovation*

A need for a project champion was highlighted in the SCE, see Table 1, and as such the requirement was brought up at the focus group discussion and a project planning meeting. The community group already practiced having project leaders on new ventures, and a project leader was promptly nominated. The project leader (project champion) was key to coordinating day-to-day operations. The project leader shared research related activities with the 13 members of the community group who had asked to be involved. The project leader also organized waste collection days and times, notified members of the research status, recorded project related measurements and encouraged the active participation of the members.

Community involvement was tracked by BSFL sale. 12 kg of BSFL produced was sold to the community, which represents 63% of the BSFL harvested. The remaining BSFL was used by the community group and for laboratory testing. The dip in BSFL production impacted customers from the community as some BSFL orders could not be fulfilled. These results confirmed community involvement.

Finally, innovation was observed in the differences between the pre-project and co-produced bioreactor and drying unit designs [57]. Innovation through co-production was achieved at the end of the study [45]. Innovation was seen in the modification of the drying unit. The original drying unit was a simplistic but crude containment system built with locally sourced wood, wire mesh and a waterproof covering. A modified drying unit was later constructed to fix design issues like durability and aesthetics. The research team designed and built the original drying unit, while *Sauti ya Jamii Kipunguni* co-designed and -produced the modified unit.

Innovation was also observed in the bioreactor leachate containment system. The system was originally made of a PVC pipe that ran from the back of the bioreactor into 19 L plastic buckets buried

behind the bioreactor. The system proved inadequate in containing the leachate. During the rainy season, the rising water table thrust the buckets to the surface, necessitating a containment system designed jointly with the community. A waterproof covering was used to protect the bioreactor contents on rainy days. Table 4 presents a summary of all the study indicators and their outcomes.

**Table 4.** Study indicators and their outcomes.

| Indicator | Data source | Result | Objective achieved |
|---|---|---|---|
| Resource recovery | Direct measurements | Resource loop identified and closed | Yes |
| Circular inputs | Direct energy measurements | No energy added to the system. Water used in cleaning bioreactor. Gasoline was needed for the motorized tricycle. | No |
| Job creation | People count | No hiring | No |
| Labor required | Work hours recording | Work hours required met | Yes |
| Community (project) champion | Project lead | Lead chosen | Yes |
| Community integration | BSFL sales | Community involved | Yes |
| Innovation | Co-production design outcomes | Modifications to bioreactor design. Drying unit design. | Yes |
| Simple BSF system | Work hours recording | Easy to maintain infrastructure | Yes |
| Minimal Machination | Direct energy measurements | Easy operations | Yes |
| Training and mentoring | Training sessions and operation shadowing | Independent management of the project by the community group | Yes |
| Satisfy livestock and farming needs | BSFL and compost production rates | Community's needs were met but only before the project handover | Partially |
| Economic viability | Sales, BSFL nutritional composition testing | Marketed products | Yes |

## 4. Discussion

Developing a closed-loop CE-based free-range BSF treatment system required iterative engagement of the research team and community to identify and address resource gaps. Tensions occurred in resolving the conventional practice of maximum outputs and operating a simple, easy-to-manage system that the community could afford. For example, the technology used in breaking biowaste, i.e., a shovel, remained unchanged despite the large portions of the compost that could not be used. The frass output was low compared to the literature because the waste was not broken into small digestible bits for the BSF larvae [1]. Another deviation from the literature was the difference in sub-Saharan African household biowaste volumes and waste reduction practices [58,59]. Waste was initially sourced from surrounding homes, but the volumes collected there were limited.

### *4.1. Study challenges*

Weather conditions significantly impacted the study's outcome. The research commenced during the dry season (September – October) and continued into the rainy season (December – March),

resulting in significant fluctuations in environmental conditions. Temperatures ranged between 27 and 40.2 °C, while humidity varied between 40–82.8%, Figure 10. During the rainy season, excessive precipitation flooded the bioreactor and resulted in the saturation of the leachate collection system. Additionally, the operational focus on fruit and vegetable biowaste led to the unintended consequence of high leachate volumes. This created an unsuitable environment for the BSFL. The optimal moisture content for BSFL is 70–79% [8], but the bioreactor recorded 100% from rain accessing the bioreactor and high moisture content like tomato.

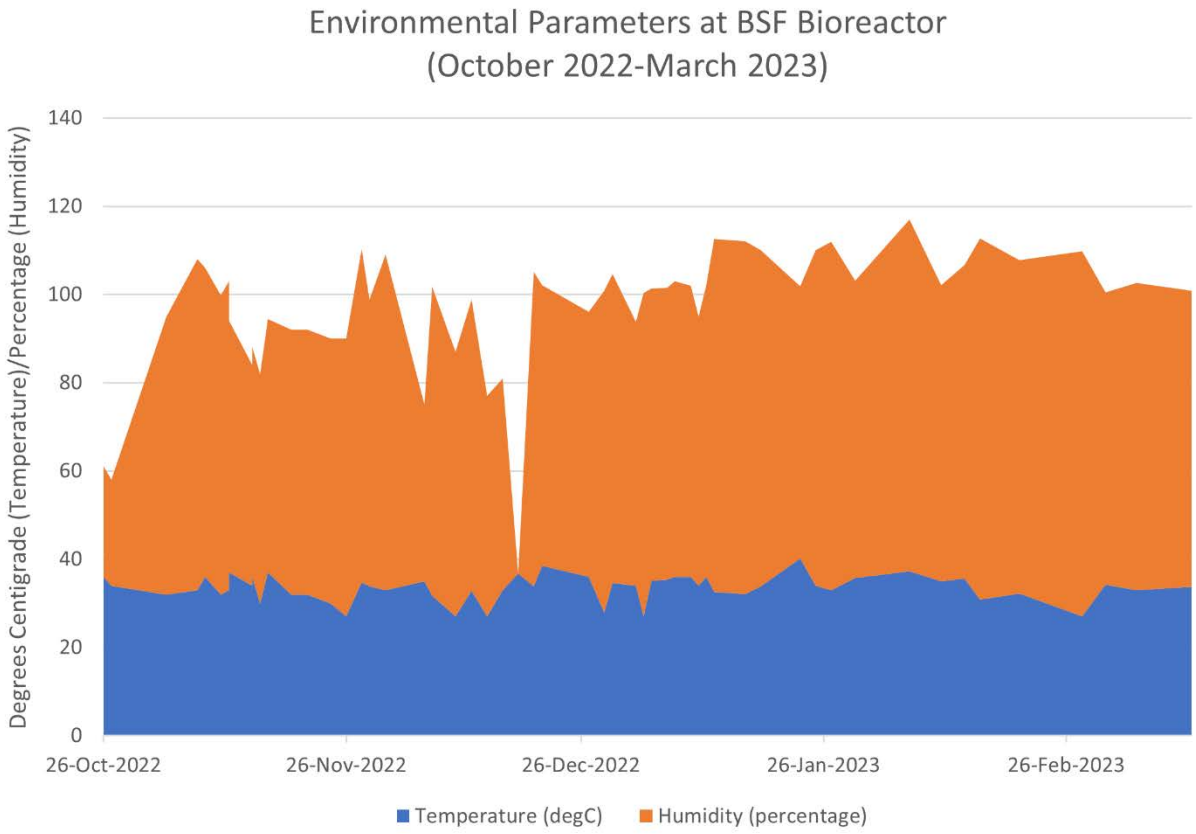



**Figure 10.** Temperature and humidity distribution at study location over the rainy season, October 2022 to March 2023.

During the dry season, algae thrived due to sunlight and warm weather, despite the addition of soap added to prevent mosquito breeding. Therefore, the water channel required weekly cleaning, adding to the work hours required and water input.

The biowaste wetness from the rain and fruit substrate also created a thriving environment for drone fly larvae [60]. Drone fly larvae are aquatic and have a respiratory appendage (tail) used to breathe in water-saturated environments [60]. As a result, the bioreactor became a conducive environment for the drone fly larvae [61]. One interesting aspect of drone fly larvae is their ability to reproduce through parthenogenesis, where a single larva splits into 7–30 daughter larvae [60,61]. The authors theorize that this enabled the drone fly larvae to rapidly increase in the bioreactor, see Figure 11. The manual removal of excess moisture in the bioreactor proved successful as the drone fly and housefly larvae population steadily decreased from day 68 while the BSFL population increased, see Figure 11.

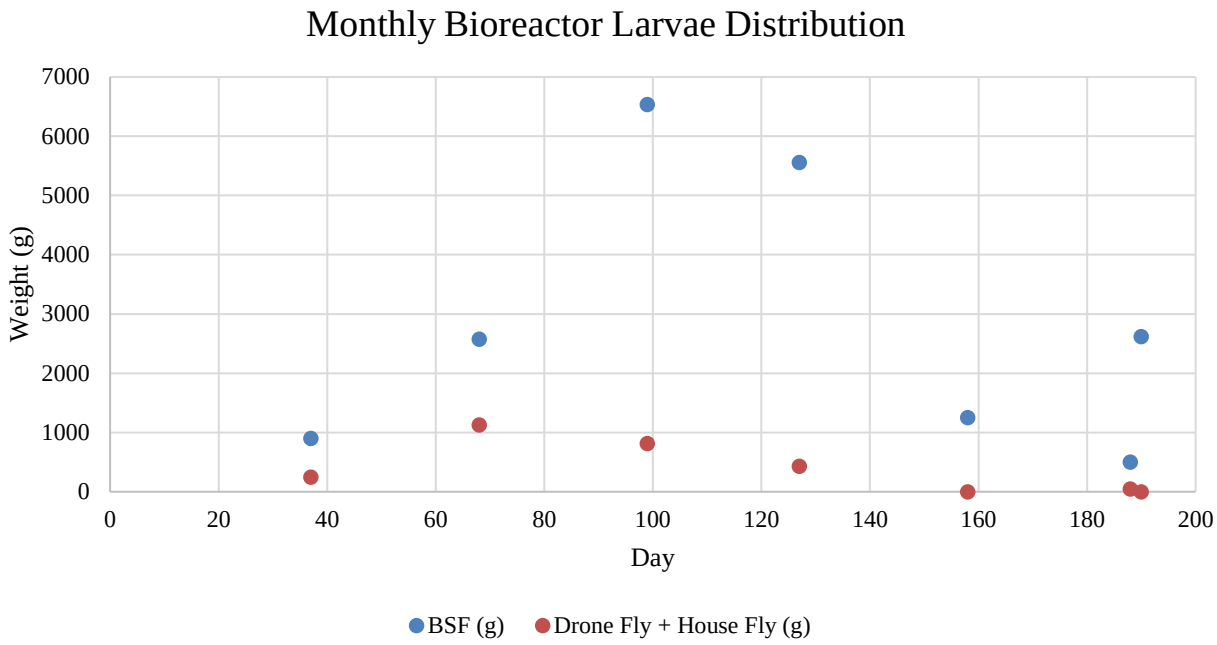



**Figure 11.** Black soldier fly larvae and drone fly and housefly population tracked by weight.

The nutritional analysis of the BSFL open system bioreactor placed the wild BSFL crude protein content at the upper range and its crude fat at the median values compared to the literature [17,54,55,62,63]. Depending on the BSFL strain, diet and testing procedures, the crude protein and fat content have been reported to range between 31–47.6% and 11.8–38.6%, respectively [22,23]. Wild BSFLs from New Zealand were found to have 50.55% crude protein and 36.38% crude fat [63]. In comparison, wild BSFL in Kenya had 38.98% crude protein and 32.62% crude fat [17].

### *4.2. Study recommendations*

The study successfully achieved the goal of harvesting BSFL free of heavy metals. However, microbiology and mycotoxin tests were not conducted but are recommended to ensure the safety of animals and humans. Furthermore, a feasibility study of the proposed bioreactor location is recommended before installing a BSF system [15]. A feasibility study would have identified the direct use of biowaste by households in the community. Amongst other things, it would have also revealed areas prone to flooding over the rainy season.

## 5. Conclusions

The case study investigated how an open BSF biowaste system could apply circular economy principles to close a resource loop in a low-income community and highlights the benefits of adopting a modified circular economy. Corn bran was substituted by BSFL as animal feed, and frass biofertilizer replaced commercial fertilizer. Thus, demonstrating circularity in the study location.

The system proposed in this study is only applicable in tropical and sub-tropical climates [14,21]. Furthermore, scaling the free-range open BSF system would pose a challenge, as it would require

implementing additional controls to maintain consistent BSFL nutritional profiles and production rates. This could prove economically unfeasible for low-income communities. On the other hand, keeping the design unchanged would require significant space which is unavailable in peri-urban locations.

Finally, although locating the bioreactor in the *Sauti ya Jamii Kipunguni* premises proved advantageous because the unit was carefully monitored, an optimal site for the bioreactor could be at the source of the waste generation, i.e., the retail fruit and vegetable market. This would eliminate the need for motorized transportation and potentially promote the diversion of greater biowaste volumes. Nonetheless, the proven use of a simple free-range open BSF system could advance CE practices in a bottom-up approach through communities in low-income communities.

## Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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## Conflict of interest

The authors declare that there is no conflict of interest.

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