



Circular Household Organic Waste Management System Using Black Soldier Flies on A Communal Scale in Rural Areas

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Abstract

Many villages in developing countries, like Indonesia, lack formal waste collection services, have minimal waste management facilities, and have low environmental awareness, leading to the accumulation of waste, especially organic waste, which negatively impacts the environment and public health. Accumulated organic waste in rural areas is a crucial issue. Previous literature explains the success of using BSF technology in organic waste processing on an industrial or individual scale, but no one has yet examined the use of BSF technology on a communal scale for household organic waste management in rural areas. This study explores the use of communal-scale BSF technology to achieve circular household organic waste management in Laras Dua Village, Indonesia. The methodology involves experiments using a 40 m² communal area with 100 selected housewives. The research results show that 74% of organic waste is converted into BSF larvae and compost. Incorporating mixed food waste (including fruits, vegetables, and cooked food) enhances larval growth compared to using only fruits and vegetables. Our discovery is that using community-based BSF technology can help manage organic waste in rural areas by turning household waste into BSF larvae, which can be used as animal feed and compost for plants. These findings are important for helping villages achieve sustainable development goals, creating chances for more research on improving processing methods, applying these models in other rural areas, and studying the economics to keep this program going.

Keywords: Black Soldier Fly, Communal Scale, Households Organic Waste, Rural Area

Introduction

The exponential growth of the human population and the corresponding rise in global prosperity have resulted in the utilization of resources surpassing their sustainable limits. Consequently, this phenomenon has contributed to a significant escalation in garbage generated worldwide (Chen *et al.*, 2020; Hoang & Fogarassy, 2020). The escalating levels of destruction are not met with adequate waste management measures, exacerbating challenges associated with waste management activities at both regional and local levels in urban and rural areas (Pöldnurd, 2015). The provision of garbage collection services in both urban and rural areas encounters a disparity, especially in transitional and developing countries (Mihai, 2017). In rural locations, there is typically a lack of emphasis on the proper collection and management of formal waste and an absence of official infrastructure dedicated to handling waste, which is more commonly found in urban settings. Consequently, the management of waste in rural areas is disregarded (Han *et al.*, 2018; Vanninen & Nissinen, 2012). This has pushed villages to manage waste in a manner that is not sustainable (Nguyen *et al.*, 2015; Siddiqui *et al.*, 2022),

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such as throwing away rubbish into bodies of water, burning trash in open spaces, and the illegal accumulation of junk (Han *et al.*, 2018; Mihai, 2017). As a result, rural people face challenges due to the deterioration of environmental factors such as water quality, air purity, soil fertility, and overall health conditions. Improper waste management practices lead to the prevalence of numerous diseases (Mihai & Grozavu, 2019).

Indonesia, as a developing nation, has also encountered the issue of waste management. The "System Information Management National Waste in 2020" report analyzes Indonesia's waste situation: waste composition is comprised chiefly of organic rubbish, accounting for 54% of the total waste. The remaining 46% comprises non-organic waste, with food waste being the predominant type at 39.30%. The sources of this waste may be attributed to household activities, specifically domestic consumption, accounting for 46% of the total waste generated (Ministry of Environment and Forestry, 2020). This issue is prevalent in large rural areas. There is a lack of sufficient facilities and methods to manage waste effectively, increasing created waste, particularly household waste (Steinhoff-Wrzeńniewska, 2015). This issue needs to be appropriately addressed (Damanhuri, 2017). Challenges related to waste management in rural areas might impede the attainment of sustainable development goals (SDG) in both villages and countries. It is worth noting that approximately 74% of the national SDG can be realized by successfully achieving SDG in rural areas (Iskandar, 2020).

Adopting circular management practices in rural regions is a feasible strategy because of its alignment with the Sustainable Development Goals (SDG 12). Implementing a circular economy in waste management entails promoting trash reduction, recycling, and using waste as a resource to establish a self-sustaining economic cycle (George, Lin & Chen, 2015; Hoa & Khanh, 2021). According to Smetana *et al.* (2016), employing this approach can minimize the environmental impact and contribute to efficient waste management practices (Smetana *et al.*, 2016). Previous studies have shown that the larva of the black soldier fly (BSF) can gather a lot of nutrients as it grows and can live on organic waste materials. According to Paz *et al.* (2015), BSF larvae employ enzymatic processes within their bodies to decrease the presence of substance pollutants in trash by approximately 50%-60%. Additionally, they can reduce nitrogen content and other mineral concentrations by approximately 40%-62% (Parra Paz, Carrejo & Gómez Rodríguez, 2015).

BSF larvae have the potential to be efficiently and economically cultivated using organic waste as a feed source (Kenis *et al.*, 2014; Pastor *et al.*, 2015; Van Huis, 2013). The larvae of BSF are known for their very efficient bioconversion capabilities since they consume a diverse range of organic materials, including discarded fruits and vegetables, leftover food, fish waste, coconut palm cake, animal manure, and human excrement (Mujahid *et al.*, 2017; St-Hilaire *et al.*, 2007). According to Siddiqui *et al.* (2022), the BSF larvae can efficiently convert organic waste into valuable biomass, contributing to biomass economics. Multiple studies have documented the capacity of BSF larvae to effectively decrease organic waste, with reductions ranging from 44% to 94% (Alvarez, 2012; Bonso, 2013). Additionally, Dortmans (2017) showed a substantial reduction of 85% in wet weight. According to Nguyen *et al.* (2015) and Gabler and Vinnerås (2014), BSF technology has been evaluated as environmentally friendly, sustainable, and conducive to promoting a positive ecological impact (Dortmans *et al.*, 2017; Gabler and Vinnerås, 2014; Nguyen *et al.*, 2015).

Several countries, including South Africa, Canada, and Ghana, have successfully implemented the BSF technology (Lohri *et al.*, 2017). Additionally, China, Korea, Vietnam, Japan, and Malaysia have effectively adopted it (Kim *et al.*, 2021). A successful study on the use of BSF in Malaysia involved processing local coconut waste as a substrate for BSF larvae. The larvae that grew on coconut waste fermented for 4 weeks had the highest growth rate, with a fat content reaching 48%, while larvae grown on non-fermented coconut waste only had a fat content of 33%. The increase in protein content of the larvae occurs with a longer fermentation duration (Mohd Noor *et al.*, 2018). Meanwhile, a study in China on the use of BSF for food waste analyzed the conversion of nitrogen, carbon, greenhouse gas emissions, and NH₃ during the waste processing. The results indicated that an important parameter affecting the process was the pH of the organic waste. The harvested BSF larvae had a wet weight ranging from 13.26 to 95.28 mg/larva, with nitrogen and carbon recycling rates of 5.40-18.93% and 1.95-13.41% from the substrate at pH levels ranging from 3.0 to 11.0 (Pang *et al.*, 2020). The utilization of previous BSF technology is centered around several areas, such as technique, method processing, process engineering, and the products of the process (Joly, 2018). In addition, BSF technology has evolved to become a valuable asset for individual landowners and businesses, regardless of their scale. Moreover, the utilization of BSF technology has expanded into other business sectors, catering to both individual entrepreneurs and large- to medium-scale industries (Joly, 2018). However, there have been

no studies regarding designing systems for waste processing with BSF technology in communal settings.

This study highlights the gap in the implementation of Black Soldier Fly technology at the communal scale, focusing on rural areas with limited waste management infrastructure. Unlike the BSF systems for households or industries, this research adapts BSF technology at the communal scale for waste management at the community level using a participatory approach, where groups of housewives are directly involved in the process, from waste collection to BSF larvae management. This experiment is tailored to the needs of rural communities and uses household organic waste, such as food scraps, fruits, and vegetables, while emphasizing the potential of BSF to reduce waste and support food security and sustainable agriculture through the production of animal feed and organic fertilizer. Focusing on the community scale, this study addresses less-explored challenges in other BSF systems, such as the integration of technology into the local socio-economic structure, accessibility for rural communities, and the long-term feasibility of BSF as a community-based organic waste management solution (Joly, 2018). Additionally, literature on utilizing BSF technology for waste management in rural communities is scarce. Consequently, the implementation of BSF technology for producing circular-based public waste management systems has yet to be suggested.

This research addresses the knowledge gap in utilizing BSF larvae for organic waste management in rural households, offering a promising solution for sustainable waste management. The use of circular economy principles in managing rural waste can be achieved through BSF technology (Bortolini *et al.*, 2020; Ojha, Bußler & Schlüter, 2020; Wang & Shelomi, 2017). This study looks into using community-based BSF technology on a larger scale to manage household organic waste in Laras Dua Village, Simalungun Regency, Indonesia, by trying out different methods. A demonstration plot covering 40m² was set up, with housewives participating in the entire process, from sorting, collection, transportation, and processing to BSF cultivation, while comparing the composition of organic waste as a substrate for the larvae.

The case study conducted in Laras Dua Village, Indonesia, demonstrates selectivity; Laras Dua Village was chosen as the research area because the village is facing waste management issues and has no available facilities for organic waste processing. However, the village community is willing to get involved in using BSF technology for organic waste processing, as well as the potential for livestock and fisheries in their village. The results of this study can apply to other rural areas that lack facilities for processing organic waste, where community groups are eager to use BSF for managing waste together; villages that have suitable environments for BSF; and villages that have opportunities for fisheries, livestock, and farming, allowing the use of BSF larvae and compost products.

Materials and Methods

Study Area

The study was conducted at Laras Dua Village in the Siantar District of the Simalungun Regency, North Sumatra Province, Indonesia (Figure 1). The population of the village amounts to 74,271 individuals. The area of the subdistrict is 10.30 km², which accounts for 13.49% of the wider subdistrict. Additionally, the subdistrict is situated at an altitude of 302 meters above sea level. There were 345 rice fields in the area, encompassing agricultural land (Indonesian Statistics, 2019). Facilities for garbage disposal, such as temporary trash storage and waste banks, are currently lacking. The study was conducted between August 2021 and August 2022.

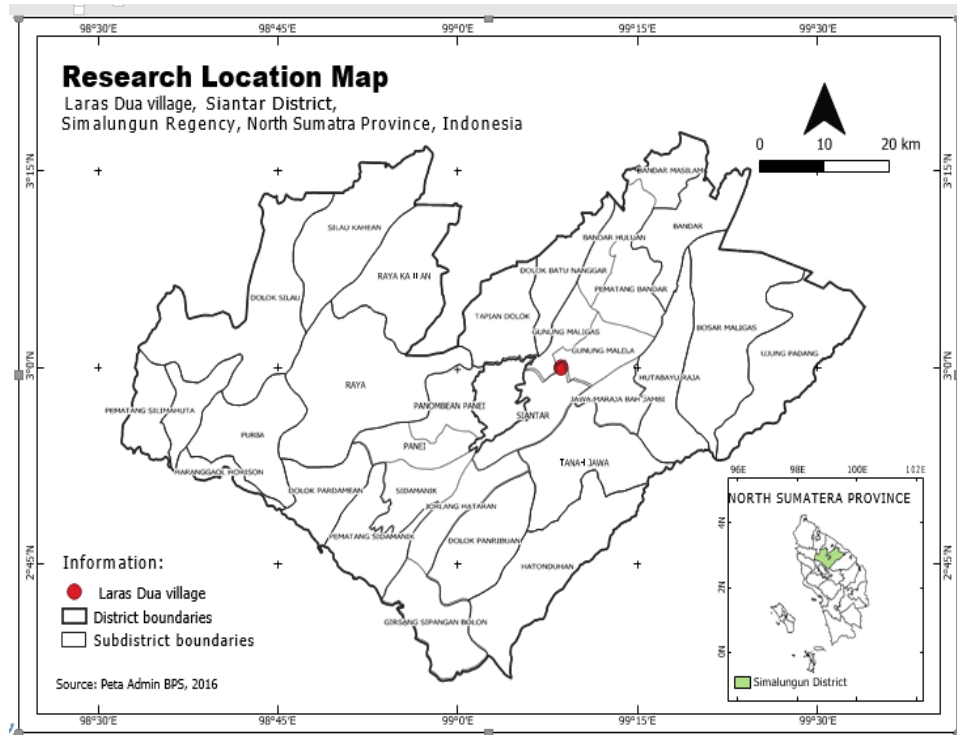


Figure 1: Map of Research Location

The research method involves an experimental setup for community-based waste management using BSF technology on a communal scale in rural areas. The study consists of two phases: first, the preparation of housewife groups to be involved in the use of communal-scale BSF technology for managing household organic waste in Laras Dua Village. Second, a plot experiment for waste processing using an experimental design for communal-scale waste management with BSF. The plot experiment aims to look at the life cycle of BSF, find the best mix of food (comparing combinations of fruits and vegetables with combinations of fruits, vegetables, and food scraps) for feeding BSF larvae, and assess how well the larvae grows. The expected outcome of this experiment is a circular household organic waste management method using communal-scale BSF technology that can be applied in rural areas.

Preparation Stage

The preparation stage includes steps such as counseling sessions, informative presentations about BSF technology, and selecting a representative sample of housewives. Counseling services were provided to housewives involved in the Family Welfare Movement regarding household waste management and introducing the BSF life cycle. The next phase of the project involves implementing waste management practices for a month using BSF larvae in Laras Dua Village. After counseling and demonstrations, interviews were conducted with the housewife group to identify and recruit those willing to participate as research subjects. The selection of housewives for the sample was done through purposive sampling, which involves identifying specific criteria aligned with the research objectives (Sugiyono, 2010). The sample size was determined in the early phase based on these criteria. These criteria include the housewives' participation in counseling sessions and demonstrations focusing on waste management utilizing BSF larvae. Additionally, the willingness of housewives to donate their household organic waste for processing and their commitment to participate in the experimental processing activities using communal-scale BSF technology were considered.

Experimental Design

The experimental setup was constructed within the premises of a residential property, encompassing an area of 40 m². This setup included a dedicated waste processing room and a separate room for maintaining the BSF population. The proximity of these two rooms facilitated the efficient management of organic waste and the convenient transfer of BSF eggs and larvae to the waste processing facility. The cultivation room for BSF is compartmentalized into five distinct sections, which include the mating cage, BSF egg hatching area, BSF larvae cultivation zone, prepupa storage system, and pupa storage facility (Dortmans *et al.*, 2017). The source of the eggs was obtained from Biomagg Maggot Bio Store

Company in Depok City, Indonesia, and then cultivated at the research location. The source of the diet is organic waste collected from households by groups of housewives. Organic waste consists of fruit waste, vegetable waste, and food scraps (rice, food scraps containing protein, fat, and others).

The organic waste recycling procedure follows the guidelines modification (Dortmans *et al.*, 2017; Lalander *et al.*, 2019; Monita *et al.*, 2017) as follows:

- a. 1 gram of BSF eggs is placed on the hatching medium, namely 500 grams of bran finely dissolved with 1 liter of clean water.
- b. Larvae are put in a larval cultivation bucket, namely a plastic bucket with a 50-liter payload with a broad part top of 69 cm, a width part bottom of 50 cm, and a height of 26 cm. The top of the bucket is closed with a net to prevent larvae exit and oviposition by flies other than BSF. BSF larvae were given to eat chopped organic rubbish until measuring 2-3 cm. Larval feeding was carried out on days 1, 5, 8, 12, 15, 18, 21, and 24. If 50% of the larvae turn into prepupae, the feeding is stopped, and the BSF life cycle lasts until all the larvae turn into prepupae.
- c. This experiment compared a mixed fruit and vegetable waste feed with a mixture of fruit, vegetable, and food waste as larvae feed to determine the best organic waste composition for BSF larvae enlargement.
- d. Visual observations were made from day 8 to day 25 until the first prepupa (dark color) appeared. On the 28th day after feeding, the larvae were separated from insect frass (digestible and undigested feed) using a 4 mm diameter sieve and then weighed to determine the weight of larval biomass and compost.
- e. Sampling and analysis: For each group, larvae samples from each larva cultivation bucket were taken randomly, washed with distilled water, weighed, and placed back in the feed bowl. When the prepupae appeared, they were removed from the treatment container and transferred to the prepupa storage room until later turned into pupae and adult flies.
- f. At the end of the feeding period, all remaining larvae and prepupae were manually removed from the waste residue and counted. Collected larvae and prepupae were weighed separately, and their mass was measured.

Data Analysis

The performance of BSF larvae in organic waste recycling was evaluated by calculating waste reduction rate, bioconversion rate, feed conversion ratio, average larval and prepupae weight, larval development time, and larval survival rate. This parameter is defined as follows:

$$\text{Reduction rate waste: } \frac{W_1 - W_2}{W_1} \times 100 \quad \text{Eq. (1)}$$

Where W_1 represents the starting weight of the waste provided as larval food, and W_2 denotes the weight of the waste measured after the completion of the larvae feeding process. A high waste reduction level number signifies good waste reduction efficiency.

$$\text{Bioconversion rate: } \frac{\text{Final weight of larval biomass}}{\text{The initial weight of the added waste}} \times 100 \quad \text{Eq. (2)}$$

Where larval biomass includes larvae and prepupae, harvested from residual waste when 50% of the larvae have turned into prepupae. A high bioconversion rate indicates good bioconversion efficiency.

$$\text{Feed Conversion Rate: } \frac{\text{Total weight of feed ingested by larval biomass}}{\text{Weight gained by larval biomass}} \quad \text{Eq. (3)}$$

The weight gain of the larvae is estimated by the initial weight of the organic waste that is put into the cultivation tank minus the weight of the larvae and prepupae at the end of the feeding period (when 50% of the larvae turn into prepupae). Likewise, the total weight of organic waste ingested by the larvae is estimated by the weight of the organic waste residue minus the initial weight of the organic waste put into the grow-out tank. A low feed conversion ratio indicates good feed conversion efficiency. Larval development time is determined by the length of time the larvae turn into 50% prepupae, while survival rate is considered as the proportion of larvae still alive at the end of the feeding period (Lalander *et al.*, 2019).

Result and Discussion

Based on the outreach material delivered to the group of housewives in Laras Dua village, the community understands the importance of processing their household organic waste and is responsible for processing their waste. Groups of rural housewives easily understand and accept BSF technology. They are willing to collect their organic waste, learn about BSF cultivation, and not feel disgusted with BSF larvae. They are even interested in using BSF larvae to process their waste.

BSF Life Cycle on a Communal Scale

The Black Soldier Fly (BSF) cultivation process is conducted in Laras Dua Village using an artificial breeding system, where BSF eggs and 5-day-old larvae are produced independently. The BSF cultivation cage measures 1x1x2 meters (Figure 2) and is equipped with a zipper to facilitate the collection of eggs and pupae. This cage is positioned in a sunlit area to promote fly mating, as recommended by Barragan-Fonseca, Dicke & van Loon (2017). To attract female flies for oviposition, a waste-based attractant, such as water with a pungent odor, is placed outside the cage, while the cage itself is sprayed with water 2-3 times daily to maintain fly hydration (Barragan-Fonseca, Dicke & van Loon, 2017). Once the eggs hatch, we transfer the newly emerged larvae to a hatching container filled with a water-dissolved bran feed mixture. These containers allow the larvae to develop for approximately ten days.

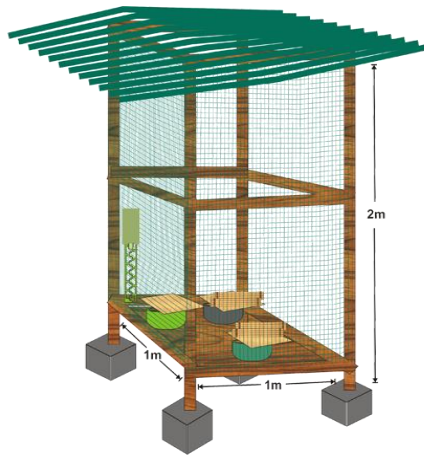


Figure 2: *BSF Cage*

Following the hatching phase, waste processing experiments are conducted in 50-liter plastic buckets, which are filled with sorted organic waste. The waste is stored for no more than 24 hours before processing. Five-day-old larvae are then fed 25 grams of organic waste, continuing until they reach the prepupal stage. These experiments are conducted in ten separate cultivation tanks, with three cycles completed over a period of two months to process a total of 750 kg of organic waste. The cultivation containers are placed on wooden storage racks (Figure 3). After 28 days, larvae are separated from the frass using a sieve to measure the biomass of the larvae and the compost produced.

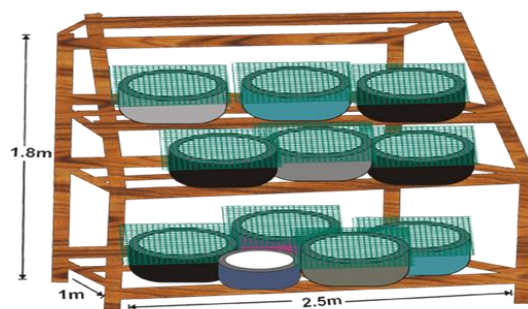


Figure 3: *Storage Rack*

A two-bucket system is employed to collect prepupae: the first bucket, containing dry bran, attracts the prepupae out of the cultivation containers. Once harvested, the prepupae are transferred to a storage container for pupation. After pupation, the pupae are reintroduced into the BSF enclosure, where newly emerged adult flies mate and lay eggs, completing the life cycle and initiating a new cycle. This system is designed to optimize space utilization and enhance the efficiency of both BSF larva production and organic waste processing. The life cycle of the BSF spans between 6 to 8.5 weeks, encompassing the egg, larva, prepupal, pupal, and adult stages (Figure 4).

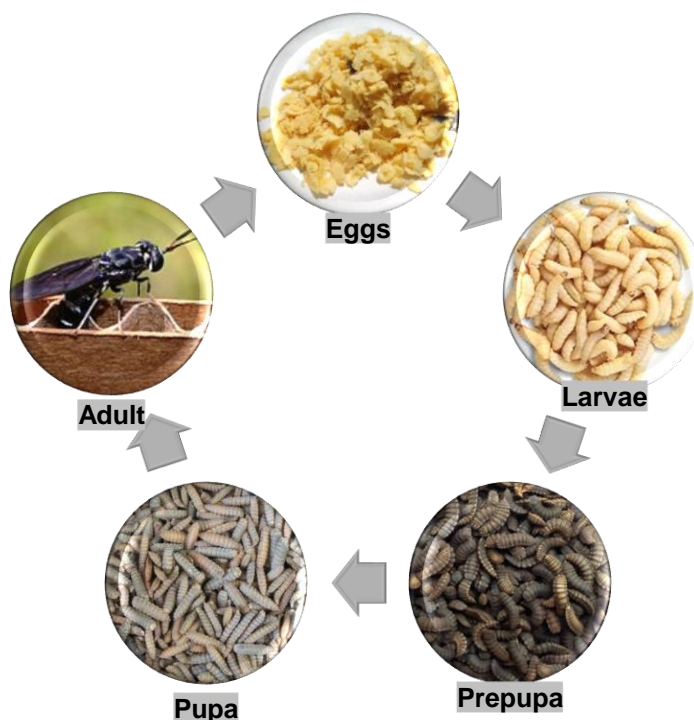


Figure 4: *The life cycle of the Black Soldier Fly (BSF)*

Figure 4 depicts the five primary phases of the Black Soldier Fly's (BSF) life cycle: egg, larvae, prepupae, pupae, and adult. The female starts the egg stage by depositing eggs close to an organic supply, which, in the right circumstances, will provide food for the larvae when they hatch in 2-4 days. According to Diener, Zurbrügg and Tockner (2009), the larval stage is the most important stage because it allows the larvae to efficiently absorb organic waste, lowering up to 50–70% of the waste mass (Diener, Zurbrügg & Tockner, 2009). The larvae are also a significant raw material for fish and cattle feed since they are high in fat (25–30%) and protein (35–45%). Following multiple instars, the larvae go to arid areas to begin the pupal stage, which, depending on humidity and temperature, lasts for seven to fourteen days. The energy gathered during the larval stage is utilized in this stage to transform into an adult fly. Adult BSF flies are harmless to people and animals since they only survive for five to eight days and concentrate on breeding rather than feeding. According to earlier studies (Newton *et al.*, 2005), these traits set BSF apart from regular houseflies because they don't carry any infections. BSF is a significant player in the management of organic waste because of its dominance in the larval stage and the sustainability of its life cycle. Because of its biological properties and financial worth, BSF has gained recognition as a creative response to environmental problems and the demand for substitute proteins.

This study examined the life cycle of BSF, from the egg stage to the adult fly. Rural communities can safely raise BSF because larvae and adult flies are not pests and do not carry pathogens. Therefore, BSF is not harmful to humans or animals, making it a safe organism for waste management and livestock feed production (Park, 2016; Ritika *et al.*, 2015). Successful breeding and mass production of

BSF are highly influenced by environmental conditions such as temperature, relative humidity, substrate moisture, sunlight exposure, and aeration (Rehman *et al.*, 2023; Singh & Kumari, 2019).

The life cycle of BSF is supported by the favorable environmental conditions at the research site, with a wide temperature range during the study from 20 to 32°C. This aligns with Singh & Kumari (2019), who explained that regions with a broader temperature range significantly promote BSF development, leading to higher populations compared to areas with narrower temperature ranges. BSF can thrive even under extreme conditions, with a life cycle lasting 1 to 2 months (Singh, Marathe & Kumari, 2022).

Waste reduction rate, bioconversion rate, and feed conversion ratio on different substrates

The performance of demonstration plot experiments to determine waste reduction rates, bioconversion rates, and feed conversion ratios on various substrates is shown in Table 1.

Table 1: Waste reduction rates, bioconversion rates, and feed conversion ratios, measured in the wet material for each substrate in the presence of BSF larvae

Feed	Waste Reduction Rate (%)	Bioconversion Rate (%)	Feed Conversion Ratio
Fruit and vegetable waste	63.33±2.60	10±0.4	6.80±0.04
Mixed fruit, vegetable, and food waste	74±0.8	13.47±0.61	5.82±0.32

According to the analytical results, the fruit and vegetable waste substrate has a feed conversion ratio of 6.80 ± 0.04 , a bioconversion rate of $10\% \pm 0.4$, and a waste reduction rate of $63.33\% \pm 2.60$. With a waste reduction rate of $74\% \pm 0.8$, a bioconversion rate of $13.47\% \pm 0.61$, and a feed conversion ratio of 5.82 ± 0.32 , the mixed substrate of fruit, vegetable, and food waste, on the other hand, demonstrated superior performance. According to this data, the mixed substrate yields better results for the BSF larvae's degradation process than the fruit and vegetable waste substrate alone. While the higher bioconversion rate demonstrates that BSF larvae can convert more organic material into their body biomass, the high waste reduction rate in the mixed substrate suggests greater efficiency in lowering waste volume. Better substrate utilization efficiency by the larvae is also shown by a reduced feed conversion ratio on the mixed substrate. All things considered, our findings demonstrate the potential of BSF larvae in the management of organic waste, especially on substrates with varied compositions. This has consequences for both the generation of high-value biomass and sustainable waste management techniques.

The waste reduction rate, bioconversion rate, and feed conversion ratio are important parameters in research on the efficiency of larvae in processing organic waste. The waste reduction rate, measured through the waste reduction rate, reflects the larvae's ability to reduce the substrate, with higher values indicating better efficiency in reducing organic material. Meanwhile, the bioconversion rate shows how well the larvae turn feed into their body mass, using different measures that look at how much they grow and the nutrients they contain. The feed conversion ratio shows how effectively the larvae can convert the feed consumed into larval mass, measured as a percentage of the total feed consumed. These parameters are crucial for assessing how effective larvae are in performing the bioconversion of organic waste into useful products (Naser El Deen *et al.*, 2023). The substrate characteristics show a positive relationship with various parameters, such as fresh larval weight, wet prepupal weight, larval length, protein conversion, substrate reduction rate, and waste reduction index (Hosseindoust *et al.*, 2024). The survival rate for the mixture of fruit waste, vegetables, and food scraps was higher than for the fruit and vegetable waste mixture, although not significantly. This study agrees with Seyedalmoosavi *et al.* (2022) and Eggink, Donoso & Dalsgaard (2023), which say that choosing the right materials for BSF larval cultivation greatly affects how well they grow and how efficiently they convert feed.

Daily Weight of BSF Larvae on Two Different Substrates

The mixture of organic waste, including fruits, vegetables, and food scraps, contains various essential components such as carbohydrates, proteins, fats, energy, and vitamins. The capacity of BSF larvae to facilitate the breakdown of organic waste results in the production of BSF larvae biomass with nutritional characteristics that are beneficial for use as animal feed.

The daily development of BSF larvae on different feeds is shown in Figure 5.

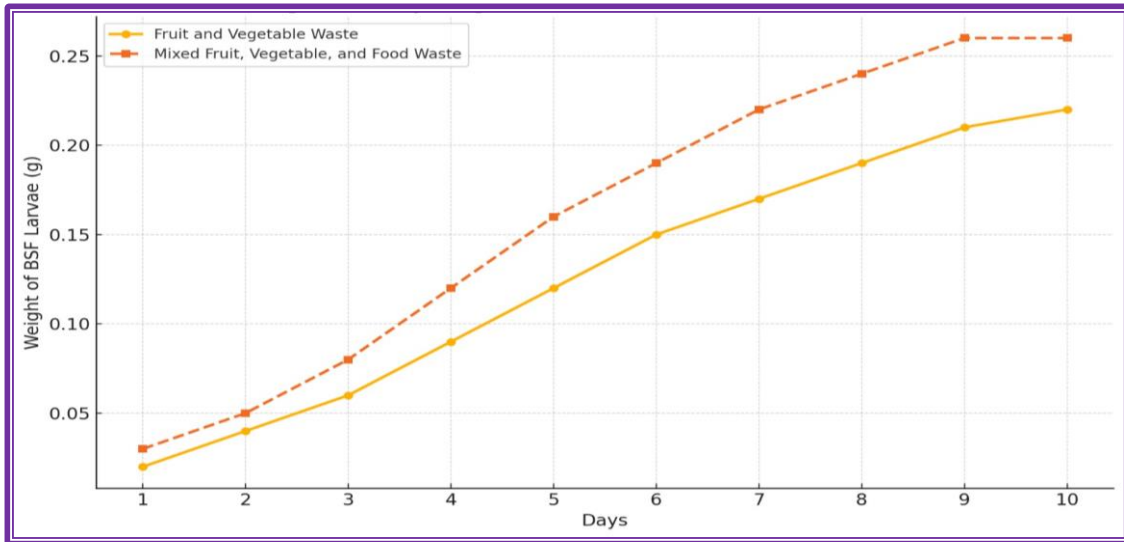


Figure 5: Daily weight of BSF larvae with two different feeds

Figure 5 shows the daily weight differences of Black Soldier Fly (BSF) larvae fed two different types of feed, namely fruit and vegetable waste and a mixture of fruit, vegetable, and food waste. This graph illustrates the growth pattern of the larvae during the feeding period and provides insights into the efficiency of both types of substrates in supporting larval weight gain. Based on the graph, the larvae fed with a waste mixture showed a higher daily weight increase compared to the larvae that were only fed with fruit and vegetable waste. In the early days, both groups of larvae showed similar growth trends, but over time, the growth of the larvae fed with the waste mixture increased more sharply. This evidence indicates that the waste mixture provides a more diverse and complete range of nutrients, allowing the larvae to utilize the feed more efficiently. At the end of the observation period, the weight of the larvae fed with the waste mixture was much greater compared to the larvae fed with fruit and vegetable waste. This difference can be attributed to the richer nutritional composition in the waste mixture, such as a more balanced content of protein, fat, and carbohydrates.

The diversity of substrates in the waste mixture may also increase the availability of energy and essential nutrients for larval growth, thereby supporting the more optimal development of larval biomass. These results highlight the importance of selecting the right substrate to support BSF larva cultivation. By using a mixture of waste, larval productivity can be increased, which in turn can enhance the economic value and efficiency of the BSF-based waste processing system. Moreover, these results reinforce the argument that diverse organic waste has great potential as an efficient feed source in supporting environmental sustainability efforts through better waste management. These findings are consistent with previous studies that show the nutritional composition of feed plays a key role in determining larval biomass production (Shah & Hayat, 2024).

Survival Rate, Development Time, Weight of BSF Larvae, and Prepupae on Different Substrates

The of survival rate, development time, weight of BSF larvae, and prepupae on different substrates is shown in Table 2.

Table 2: Survival rate, development time, weight of BSF larvae, and prepupae with different feeds

Feed	Larval Survival Rate (%)	Time for First Prepupa to Appear	Time For Pupa to develop by 50%	Larval Weight at the end of Feeding Period (g)	Prepupa Weight (g)
Fruit and vegetable waste	90.35±1.13	20±1	36±1	0.217±0.03	0.162±0.002
Mixed fruit, vegetable, and food waste	92.67±0.35	11±1	29±1	0.259±0.002	0.202±0.001

The survival rate of larvae on fruit and vegetable waste substrates is 90.35% ± 1.13, while on mixed waste substrates, it increases to 92.67% ± 0.35. This evidence indicates that the waste mixture provides more supportive conditions for BSF larvae to survive. In terms of development time, the waste mixture resulted in a shorter time for the appearance of the first prepupa, which was 11 ± 1 days, compared to fruit and vegetable waste, which took 20 ± 1 days. Additionally, it takes 29 ± 1 days for 50% of the larvae to reach the pupal stage on the waste mixture, which is faster than the 36 ± 1 days on the fruit and vegetable waste substrate. This development speed indicates that the waste mixture provides a better source of nutrients, which accelerates the larval life cycle. The weight of the larvae and prepupae also showed better results on the waste mixture. The weight of the larvae at the end of the feeding period was 0.259 ± 0.002 g, higher than 0.217 ± 0.03 g on fruit and vegetable waste. This study aligns with the findings of Lalander *et al.* (2019), who elucidated that the rate of larval development in fruit and vegetable waste is comparatively slower when compared to food waste (Lalander *et al.*, 2019). Similarly, the weight of the prepupa in the waste mixture reached 0.202 ± 0.001 g, whereas in the fruit and vegetable waste it was only 0.162 ± 0.002 g. The higher prepupa weight suggests that the larvae were able to convert more of the organic material into body mass, reflecting the improved efficiency of the mixed substrate (Han *et al.*, 2018). This difference highlights that a mixture of organic waste with a broader variation provides better nutrition for Black Soldier Fly larvae, thereby improving the efficiency of waste conversion into high-value biomass. These findings are relevant for organic waste management based on BSF technology at both communal and industrial scales.

Substantial variations in survival rates, larval and prepupal weight, and larval length are associated with different substrate sources. Substrates like feed waste, fermentation leftovers, food scraps, fruits, and manure help BSF larvae survive better than those from vegetables and animals, showing they are more nutritious and appealing to the larvae. These substrates may contain a more balanced composition of macro- and micronutrients, along with various bioavailable compounds that meet the nutritional needs of growing larvae (Eggink, Donoso & Dalsgaard, 2023; Hosseindoust *et al.*, 2024; Seyedalmoosavi *et al.*, 2022). This study focuses on the implementation of BSF technology at a community scale in rural areas, which differs from previous studies that have concentrated more on waste management in urban areas or at the individual scale. The community-based approach, which involves housewives as the main actors in waste management, is a unique aspect that has not been widely studied. The use of communal-scale BSF technology focuses on involving the community in waste sorting, collection, and processing. There are community groups involved in managing and overseeing each stage of the waste processing process effectively. The communal scale aims to make it easier to collect organic waste on a larger scale. This approach ensures the sustainability of BSF technology in waste processing, as one of the challenges of using BSF technology is ensuring that fresh organic waste is consistently available every day at low costs (Dortmans *et al.*, 2017). Furthermore, the communal scale has the advantage of having rotating team members, which ensures effective operations and supervision, allowing each stage of the process to be carried out accurately, making it easier to control the quality of organic waste, and producing larger biomass output. Community involvement supports the success of the communal scale. Regular training efforts on BSF technology use can expose more rural communities to its understanding. Implementing BSF technology at a communal scale for waste processing shows greater profitability compared to individual implementation at the household level. The individual scale has drawbacks because it cannot guarantee an adequate supply of organic waste, the procedures for feeding organic waste to larvae are not uniform, and compliance with the procedures for feeding waste to larvae cannot be controlled (Mahmood, 2020).

This study talks about the difficulties in reaching the Sustainable Development Goals (SDGs), using communal-scale BSF technology as an example of better waste management in rural areas. This technology helps reduce waste and repurpose it for useful purposes, following the circular economy ideas in SDG 12 (Responsible Consumption and Production). BSF technology can provide economic

benefits for rural communities, such as reducing livestock and fish feed costs, which can increase household income and reduce poverty. This presents an opportunity to enhance the economic well-being of rural communities through more efficient waste management, as outlined in SDG 1 (No Poverty). By using BSF technology to manage organic waste, it has the potential to reduce pollution and improve water quality in rural areas, supporting better access to clean water and sanitation and addressing SDG 6 (Clean Water and Sanitation) (Manzoor *et al.*, 2024).

The findings of this paper show that BSF technology can be implemented effectively in processing household organic waste in rural areas on a community basis using a communal scale. BSF technology enables circular waste processing, converting household organic waste into products like larvae and compost, which are then used in livestock and fisheries. The implementation of a community-based system for managing circular household waste has the potential to address waste management challenges along the whole waste stream, from its origin to its final disposal. Moreover, this approach can provide circular economic benefits for rural areas, such as reducing waste management costs, increasing community income due to BSF larvae products that can reduce the cost of purchasing more expensive animal feed, and enhancing productivity. Thus, the use of communal-scale BSF technology has the potential to support fisheries, livestock, and agriculture activities, which are key potentials in rural areas, and contribute to achieving sustainable development goals in rural areas (Siddiqui *et al.*, 2022; Van Huis, 2013). This study found that communal-scale Black Soldier Fly technology for circular household organic waste processing is highly effective in rural areas due to the abundance of household organic waste as BSF larvae substrate, the presence of community groups open to adopting and utilizing BSF technology, and the ability to market waste processing products in rural areas. Efforts to increase community involvement can be made by providing training on the use of BSF larvae, processing animal feed products from BSF larvae, and other related topics to rural communities. The experimental results show that a mixed substrate of fruit, vegetable, and food waste provides optimal results, with a waste reduction rate of 74%, a bioconversion rate of 13.47%, and the lowest feed conversion ratio of 5.82%. Larvae fed with the mixed substrate showed faster growth and larger larvae and prepupa weights compared to other substrates, suggesting that the use of mixed substrates such as fruit, vegetable, and food waste is recommended for BSF larvae rearing.

Conclusion

This study offers a new approach to applying BSF technology on a communal scale, which differs from previous studies that focused more on individual or urban scales. But there are limits, like not evaluating variables like feeding frequency and larval density, which may affect processing efficiency. Challenges such as scalability, costs, and the need for training procurement are important considerations for implementing communal-scale systems. Therefore, it is necessary to think about financing aspects for the future adoption of communal-scale BSF technology. Additionally, adapting the results of this study to other rural locations may require modifications depending on the waste composition and local environmental conditions. The study does not evaluate the economic viability or cost-effectiveness of implementing BSF technology at a larger scale. Future research is needed to optimize variables such as exploring the impact of variables like larval density, feeding frequency, and environmental settings on the waste processing efficiency of BSF. Furthermore, it is necessary to develop a model for replicating communal-scale systems for other rural areas, conduct economic studies to ensure the long-term sustainability of this program, and compare different waste processing technologies or assess long-term sustainability. These findings provide an important contribution to achieving sustainable development goals at the village level through a circular economy approach to waste management.

Conflict of Interest

The authors declare there is no conflict of interest.

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