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Harnessing black soldier flies for eco-friendly food waste treatment: A case study from Semarang city

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ABSTRACT

Food waste constitutes a significant environmental and socio-economic challenge, particularly in rapidly urbanizing regions such as Semarang, Indonesia. Conventional food waste management practices primarily landfilling and incineration are increasingly regarded as unsustainable due to their contribution to greenhouse gas emissions, soil degradation, and limited resource recovery. This study aims to assess and compare the environmental and economic performance of two alternative waste treatment strategies: black soldier fly (BSF) bioconversion and traditional composting. A life cycle assessment (LCA) was conducted using a cradle-to-gate system boundary and a functional unit of 1 metric ton of food waste, evaluating impact categories including global warming potential (GWP), eutrophication, acidification, and human toxicity. The analysis revealed that BSF treatment significantly outperforms composting in terms of environmental impact. Specifically, the global warming potential associated with BSF treatment was estimated at 30.61 kg CO_2-eq/t, compared to 490.3 kg CO_2-eq/t for composting. Similar reductions were observed across all other impact categories. An accompanying life cycle cost (LCC) analysis demonstrated that the BSF-based system is economically advantageous, with estimated potential revenues reaching USD 733.45 per ton, derived from the sale of larvae (as animal feed) and frass (as biofertilizer). This research is constrained by the use of modeled scenarios based on localized experimental data, and does not yet incorporate dynamic operational variables or social acceptance considerations. Nevertheless, the findings provide robust evidence for the environmental and economic feasibility of BSF-based food waste treatment in urban contexts. The originality of this study lies in its application of an integrated LCA–LCC framework to evaluate insect-based waste valorization in a tropical, developing-country setting. The results offer valuable insights for municipal authorities and policymakers aiming to implement circular economy principles in sustainable urban waste management.

Keywords: black soldier fly, Semarang city, life cycle analysis, eco-friendly.

INTRODUCTION

Food waste is a critical global issue that continues to worsen, resulting in substantial environmental, social, and economic consequences (Kurniawan et al., 2022). As urbanization and population growth accelerate, cities are under increasing pressure to manage their waste streams, with food waste constituting a significant portion (Escapa et al., 2019). This issue is especially germane in Semarang, Indonesia, where accelerated urbanization and shifting consumption patterns exacerbate the strain on waste management infrastructure. In addition to not addressing the basis of the issue, conventional ways of treating food waste, such as landfilling and incineration, also contribute to greenhouse gas emissions, soil deterioration, and other environmental risks. The Black Soldier Fly, also known scientifically as *Hermetia illucens*, has gained increasing recognition for its larvae's remarkable ability to convert organic refuse into valuable resources (Salam et al., 2024). The need of adopting sustainable waste management techniques is highlighted by examining the environmental repercussions of food waste, including increased greenhouse gas emissions, land and water pollution, and loss of biodiversity (Hadiwidodo et al., 2023; Salam et al., 2022). In addition, the social and economic aspects of food waste, such as its effects on food security, resource depletion, and financial costs, are discussed to underscore the complexity of this issue (Budihardjo et al., 2023). The specific challenges Semarang City faces in managing its food waste are highlighted in the context of the global situation. Rapid urbanization, a growing population, and a shift in consumer behaviors have all contributed to an increase in waste production in the city, necessitating innovative recycling and reuse strategies (Aguiar et al., 2022).

The life cycle of the black soldier fly (BSF), focusing particularly on the reproductive efficacy of adult flies and the larval maturation phase, plays an essential role in determining its effectiveness in bioconverting organic waste (Priyambada et al., 2021). This understanding forms a scientific basis for evaluating the potential of BSF in organic waste bioconversion. Research by Mertenat et al. (2019b) in Siduarjo, Indonesia. Analyzing the BSF life cycle is a crucial aspect of sustainable food waste management efforts. BSF adult flies play an important role in the highly efficient reproductive process, ensuring population continuity. Meanwhile, larval development stands out as a critical element in processing organic waste, helping to convert it into valuable resources. Through an emphasis on reproductive effectiveness and larval development, the BSF life cycle in Siduarjo provides the foundation for innovative solutions in environmentally friendly food waste management. The larvae's extraordinary feeding preferences and efficiency in digesting a broad variety of organic waste materials, including kitchen scraps, fruits, and vegetables, are investigated. These characteristics make BSF larvae excellent candidates for transforming dietary waste into valuable resources, such as protein-rich larvae and nutrient-rich frass (Lu et al., 2022). Therefore, extensive research is conducted to evaluate the viability of a BSF-based food refuse treatment system in the city of Semarang. Analyses of the scalability and adaptability of BSF larvae production are conducted, taking into account the amount of food refuse generated in the city and the available space for breeding facilities (Van et al., 2022). A comprehensive economic analysis is performed to evaluate the costs of BSF-based treatment with conventional methods composting.

A comprehensive comparative analysis was conducted to evaluate the environmental impacts of BSF-based food waste treatment relative to conventional composting methods. This analysis was motivated by the potential of both systems to reduce environmental burdens, particularly in terms of greenhouse gas emissions and reduced reliance on landfilling. Consistent with previous studies, the results indicated that greenhouse gas emissions from organic waste decomposition can be minimized through BSF and composting systems, thereby reducing the environmental footprint by an estimated 40–60% (Kragt et al., 2023). Life cycle assessment (LCA) is used to thoroughly evaluate the effects of implementing a BSF-based food waste treatment system on the natural environment (Bouwman et al., 2022). Moreover, both systems demonstrated the potential to achieve significant environmental benefits with relatively minimal investment, making them viable for implementation in resource-constrained urban settings such as Semarang.

The advantages of BSF-based food waste treatment are known, but so are the difficulties and impediments to its widespread use. Permits and approvals needed for insect-based garbage management are covered, along with other regulatory and legal considerations (Niassy et al., 2022). Additionally, public awareness and perception of the use of insects for waste management are investigated, as they can have a significant impact on the implementation's success (Bohm et al., 2023). Important components of the operational infrastructure, such as breeding facilities and waste collection systems, are also considered (Roy et al., 2023).

Therefore, the present study aims to evaluate the technical, environmental, and economic feasibility of a BSF-based food waste treatment system in Semarang, Indonesia, in comparison with conventional composting methods. Through applying LCA and cost analysis, this research addresses a critical knowledge gap in the local implementation of insect-based waste management in Southeast Asia. Specifically, the study seeks to determine whether BSF treatment offers a superior waste management solution in terms of environmental performance and cost-effectiveness.

This study hypothesizes that BSF-based systems will demonstrate lower environmental impact and comparable or reduced operational costs, supporting their potential for large-scale urban application.

METHODS AND MATERIAL

Study area

Figure 1 shows research location on Diponegoro University, Semarang, located in Central Java, Indonesia, was chosen as the study area due to its high urbanization, population density, and waste generation rate. It represents a city center struggling with the issue of food refuse management. The institution shows its commitment to sustainability and boosting academic-local government partnership by examining BSF's food waste management. Previously sorted samples of food refused from cantons, households, and restaurants were collected from a variety of sources. To ensure that the sample is representative of Semarang's food waste stream. Sample collection over a specified time period, with receptacles at various locations chosen at random to avoid bias. Triplicate samples were collected to ensure reliability and accuracy.

Black fly rearing and breeding facilities

By introducing selected adult flies into a breeding chamber containing optimal conditions, stable and healthy BSF management sites were chosen. To assure genetic diversity, the flies are obtained from reliable suppliers. BSF larvae are maintained in controlled environmental conditions, with temperatures between 28 and 32 degrees Celsius and humidity levels between 60 and 80 percent. A substrate mixture separated, incorporating organic waste materials, primarily sourced from canteen discards like fruit and vegetable scraps. To ensure accuracy, the proportions of these components are carefully measured. The substrate mixture was formulated based on previous research and the regional availability of organic waste. Research from Hosseindoust et al. (2023), the following factors play an important role. As the main ingredient, organic waste from the canteen such as fruit, vegetable and other organic material remains provides a rich and diverse source of nutrients for BSF. The carbon and nitrogen content needs to be maintained in balance to provide an environment that suits the metabolic needs of BSF. Some additional materials, such as agricultural waste or fiber-rich plant residues, can be included to provide structure and improve the carbon balance in the substrate.

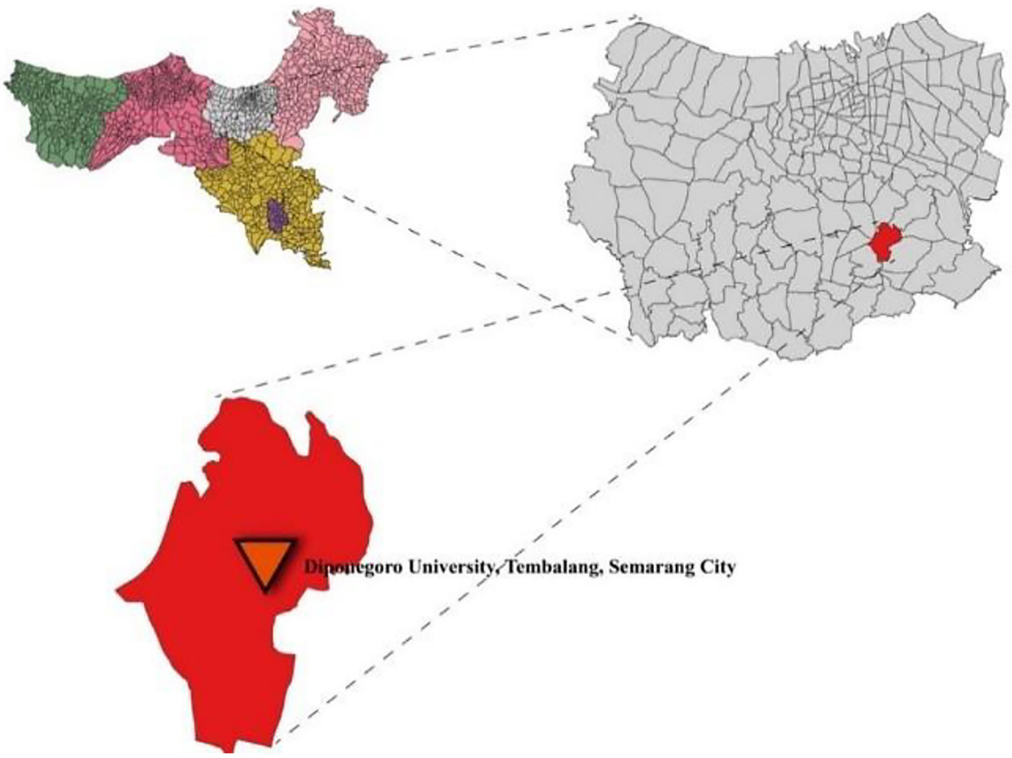

Figure 1. Study location area

Substrate moisture must also be maintained to suit the hydration needs of BSF. Monitoring stable temperatures and environmental conditions that do not inhibit the activity of BSF larvae are also important factors. Overall, successful substrate formulations for BSF carefully combine varying organic wastes, creating an environment that supports rapid growth and high nutrient accumulation in BSF larvae. The proportions of each ingredient are optimized to provide a nutrient-rich and conducive environment for larval development (Panikkar et al., 2022). By carefully adjusting the ratios of food waste from the canteen, which serves as the primary source of nutrients, the formulation aims to offer a diverse array of essential elements necessary for larval development. The balance between carbon-rich and nitrogen-rich components is a key consideration, ensuring that the substrate provides an ideal environment for the larvae to efficiently break down organic matter (Siddiqui et al., 2023).The moisture content is also meticulously managed to meet the hydration needs of the larvae, fostering a habitat that aligns with their natural preferences. Additionally, maintaining stable temperature conditions and creating an environment free from potential stressors further optimizes the substrate for larval growth. Upon reaching the desired developmental stage, adult BSF larvae are harvested (Figure 2).

Feeding trials and conversion food waste

In a randomized, controlled experiment, the feeding of food waste decomposition was evaluated. The food waste samples were separated into treatment and control groups based on the presence or absence of BSF larvae. Multiple replicates were conducted for each treatment and control group to account for variance (Curtis et al., 2022). Food waste samples are weighed and placed in a distinct room containing BSF larvae. Under controlled conditions, the larvae are permitted to subsist on the waste for a certain period of time. During feeding trials, degradation and conversion rates of food refuse were regularly monitored. Feeding trial would typically involve offering them a predetermined quantity and composition of organic waste, such as food waste. Researchers or practitioners would then systematically observe and measure factors like the degradation and conversion rates of the waste, the growth rate of the larvae, and any other relevant metrics. This allows for an assessment of how well the larvae can process the provided food source and convert it into biomass or other desired outcomes, such as compost or animal feed (Figure 3).

Primary data collection in this study was conducted through a series of experiments designed to obtain the main inventory values from the processing of 1 ton of food waste. All data marked as Existing in the LCI Table are the results of direct measurements by researchers, while the values with references are taken from literature and databases used in LCA. The experiments began with the collection of food waste samples from local sources on campus. The samples were then sorted from contaminants, chopped, and homogenized before being fed into the experimental unit. The amount of material used in each replication was normalized to be equivalent to 1 ton of raw material, in accordance with the functional unit in this study. Once the materials were ready, the BSF cultivation experiment was conducted in a maintenance room with a temperature ranging from 28–32 °C and humidity of 60–80%. These conditions were monitored periodically using calibrated

Figure 2. BSF egg-laying media

Figure 3. Bioconversion process or maggot feeding process

thermometers and hygrometers. The larvae were then inoculated onto the substrate at a uniform density between replicates. At this stage, the entire maintenance process up to harvest was carried out as is common practice in BSF facilities, but all final results, especially the larval mass and frass/compost yield, were measured independently by the researchers. The larval yield obtained from the experiment, amounting to 20 kg per ton of food waste, and the 150 kg of compost residue are recorded as primary data (Existing). The volume of wastewater from the harvesting process, namely 1.19 L, is also a direct measurement result.

Water and energy requirements for several stages were calculated based on actual usage records. Water used in the harvesting process was recorded at 664 L, while electricity consumption for equipment such as blowers, lights, and mixers followed field measurements at the electrical connection point, namely 1.76 kWh for ventilation, 1.10 kWh for lighting, 0.02 kWh for mixing, and 2.93 kWh for the harvesting process. The product separation and purification stage used an additional 0.56 kWh of electricity and a small amount of diesel fuel, approximately 0.22 L. All of this data is the result of records taken during the experiment and is marked as primary data in the table. In addition to larval output and residue, this study also produced animal feed with a mass of 350 kg per ton of food waste. This value is the result of direct weighing after the drying and purification process. For other parameters that cannot be measured directly, such as CH_4, N_2O, CO emissions, and certain equipment energy consumption factors, this study uses values available in the literature, such as Mertenat et al., Ouedraogo et al., and Recycled Organics Unit. All use of secondary data is explicitly indicated in the LCI table.

For the composting process, the primary data collected was the amount of compost produced, which was 500 kg from 1 ton of food waste, and the use of 2 L of EM4 as the composting condition applied at the research site. Meanwhile, data on diesel consumption, electricity, and gas emissions for the windrow process followed the values in the literature because not all of them could be monitored directly during the activity. The water requirement for composting, which is 38.9 L, also refers to previously reported data. All mass, volume, and energy were recorded using digital scales, water flow meters, kWh meters, and other standard measuring devices that were calibrated before use. For gas emissions, measurements were only taken on parameters that were possible with portable devices, while the rest referred to emission factors in the literature. After all primary data was collected, the values were normalized to a base of 1 ton of food waste and entered into SimaPro software. Secondary data from Ecoinvent and literature was used to complete the process inventory that was not generated from the experiment. Thus, the LCA and LCC results presented are a combination of actual experimental data in the field and supporting data from reliable sources.

Economic analysis

Costs related to BSF colony establishment and maintenance, larval development, waste conversion, and byproduct utilization got estimated (Khaekratoke et al., 2022). The costs include capital expenditure, operational expenses, and labor expenses, that show in Equation 1. To evaluate cost-effectiveness, the total cost of BSF-based food waste remediation was compared to traditional waste management methods such as composting. The approximated profit from selling BSF larvae for animal feed and frass as bio-fertilizer is based on current market prices and anticipated demand. Economic analysis using Life cycle cost (LCC) method.

$$LCC = CapEx + OpEx + LabEx \quad (1)$$

where: *CapEx* – represents the aggregate cost of capital invested throughout the operational lifespan of the waste management system, including acquisition, installation, and integration; *OpEx* – comprises the aggregate of operational expenditures, encompassing charges related to regular upkeep, repairs, energy usage, and any additional operational costs accrued throughout the waste management system's life cycle; *LabEx* – denotes the labour expenditures associated with the maintenance and administration of the waste management system, including wages, training, and other labor-related costs accrued during the operational lifetime of the system.

LCC analysis is a reliable and essential method of economic analysis utilized in a variety of industries and sectors (Keskin and Soykan, 2023). Its primary objective is to evaluate the total cost of ownership of a product, system, or asset over the entirety of its life cycle (Franzò et al., 2022). Its primary objective is to evaluate the total cost of ownership of a product, system, or asset over the entirety of its life cycle. LCC provides decision-makers with a comprehensive view of the financial ramifications of their choices by analyzing all costs, from acquisition to operation, maintenance, and disposal (Reu Junqueira et al., 2023). This long-term perspective is essential for making informed decisions and avoiding potential cost overruns or surprises later in the product's life cycle (Haron et al., 2022). LCC permits organizations to optimize their investments, identify inefficiencies, and strategically allocate resources, resulting in increased cost savings and enhanced budgeting (Pata et al., 2023).

Environmental impact assessment

To evaluate the environmental impact of BSF and Composting-based food waste treatment systems, a cradle-to-cradle LCA was conducted. To acquire a comparison of methods for managing food waste. Global warming potential, eutrophication potential, human toxicity, and acidification potential are only few of the environmental effect categories that must be considered to fully grasp the system's environmental footprint (Jang et al., 2022). The inputs of both composting and raising larvae are measured. Data used in the LCA were obtained exclusively from laboratory experiments, primary measurements, and peer-reviewed scientific literature, and no survey-based data were used. In addition, the selection of impact categories is subjective and subject to the priorities of the involved stakeholders (Kiser and Otero, 2023). This could result in cherry-picking data to present a favorable picture or concentrating exclusively on certain impacts while downplaying others, thereby undermining the actual environmental consequences. The reliance on historical data, which may not accurately reflect future scenarios and technological advancements, is another limitation (M Alshater, 2022). LCA's inability to anticipate emerging environmental issues or contemplate potential innovations hinders its capacity to promote truly sustainable practices (Santa-Maria et al., 2022). In addition, the LCA process can be resource-intensive, necessitating extensive data collection and complex modeling, making it inaccessible to smaller businesses and developing nations and perpetuating environmental responsibility disparities.

Goal, scope and functional unit

The purpose of this research is to carry out LCA from BSF processing and composting as much as 1 ton of food waste. Therefore, the selection of a functional unit (FU) of 1 ton of food waste management in order to facilitate comparison.

System boundaries

All inputs and outputs associated with BSF and Composting based food waste treatment systems are included in the system boundary for environmental impact assessment (Ferronato et al., 2023). Inputs consist of the resources, materials, and energy required for larval rearing, dietary waste conversion, and byproduct utilization (Wehry et al., 2022). In addition to composting, outputs include reductions in food waste, harvested BSF larvae, and nutrient-rich frass, as well as environmental emissions or releases during life cycle stages. Figures 4 and 5 depict the system of boundaries.

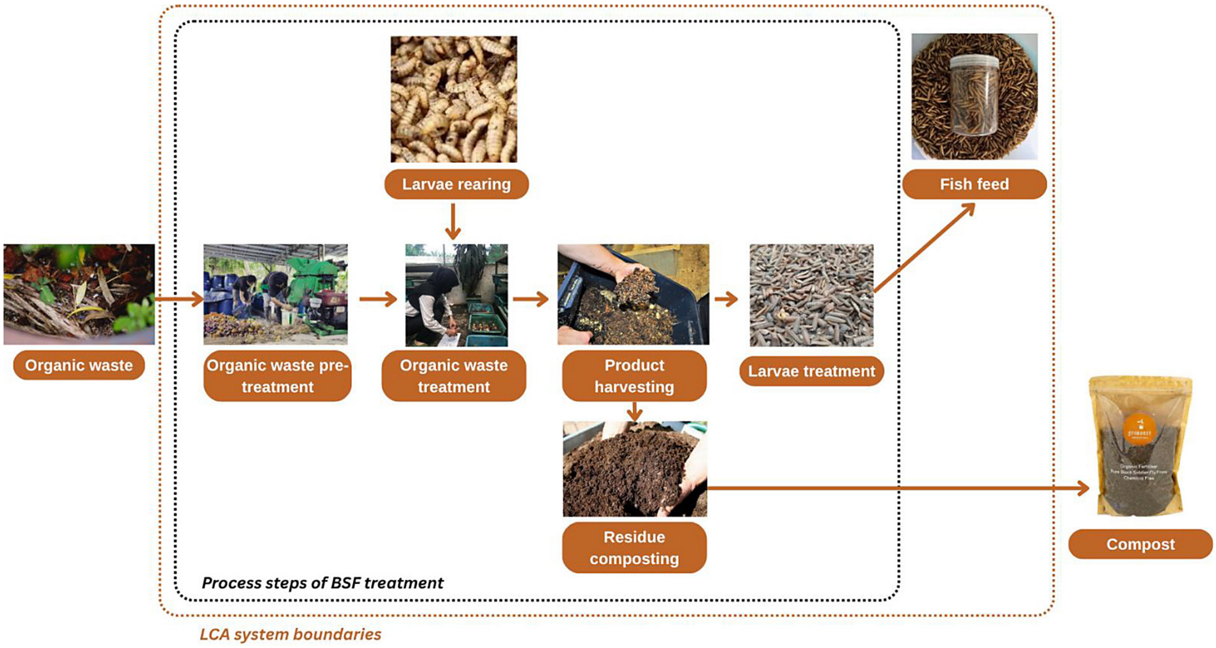

Figure 4. System boundaries black soldier fly

Figure 5. System boundaries composting

Life cycle inventory

Life cycle inventory (LCI) is the process of accumulating data on all inputs and outputs associated with each life cycle stage of a BSF and composting-based food waste treatment system (Saavedra-Rubio et al., 2022). Data were collected exclusively from experimental measurements and peer-reviewed scientific literature, ensuring compliance with journal policy. The LCI contains data on energy consumption, inputs of basic materials, water usage, and emissions (Martin-Rios et al., 2023). In this study, the LCI was developed using primary data obtained directly from experimental trials (e.g., feedstock input, larval yield, energy and water consumption) and secondary data sourced exclusively from peer-reviewed scientific literature and standardized LCI databases such as Ecoinvent 3.8. No survey-based data or governmental reports were used.

Primary data were collected during BSF rearing and composting experiments conducted on-site, including measurements of input materials, electricity and water usage, and final product outputs (e.g., larvae, compost, frass). Secondary data, such as emission factors (e.g., CH_4, N_2O, CO_2) and energy use in equipment operations, were sourced from Mertenat et al. (2019a), Ouedraogo et al. (2021), and from a published LCI dataset Recycled Organics Unit (2006). All inventory data were normalized to the functional unit of 1 metric ton of food waste treated, allowing for a direct comparison between systems. Tables 1 and 2 summarize the detailed LCI for BSF-based processing and composting, respectively, indicating the origin of each data point either from our experimental results ("Existing") or referenced literature sources. These inventories were used as the basis for the environmental impact calculations in the life cycle assessment.

Interpretation result

This analysis uses Simapro 8.0.1 software with the results of the analysis shown in Figure 4. Simapro is a popular and highly regarded software application designed specifically for LCA studies (Fransiscus et al., 2023). The environmental impact assessment applied the ReCiPe 2016 Midpoint (H) method to evaluate categories such as global warming potential, eutrophication, acidification, and human toxicity. LCI data were obtained from two main sources: (1) primary data collected during the BSF and composting experiments (e.g., electricity use, water consumption, larval yield, compost output), and (2) secondary data sourced from the Ecoinvent 3.8 database integrated into SimaPro. This database provided background data for materials, energy inputs, and emissions, including grid electricity, diesel fuel, and transportation processes (Spreafico et al., 2023). Each treatment scenario was modeled according to a functional unit of 1 ton of food waste treated, with system boundaries defined from waste collection through to product output (larvae or compost). The results were analyzed comparatively to identify which system had lower environmental impacts. All model assumptions, data sources, and calculation procedures were documented within the software to ensure transparency and reproducibility in accordance with ISO 14040/44 standards (Culaba et al., 2022; Steubing et al., 2022).

Table 1. Inventory of black soldier fly processing methods

Stage	Input name	Input	Output	Unit	References
Rearing	Food waste	1		t	Fungsional Unit
	Water	1.19		L	(Mertenat et al., 2019a)
	Ventilation	1.76		kWh	(Mertenat et al., 2019a)
	Lighting	1.10		kWh	(Mertenat et al., 2019a)
	Mixing	0.02		kWh	(Mertenat et al., 2019a)
	Chicken feed	3.1		kg	(Mertenat et al., 2019a)
	CH_4		0.4	g/t FW	(Mertenat et al., 2019a)
	N_2O		8.6	g/t FW	(Mertenat et al., 2019a)
	CO		630	g/t FW	(Mertenat et al., 2019a)
	Larva	20		kg	Existing
	Waste water		1.19	L	Existing
Waste pre-processing	-	-	-	-	(Mertenat et al., 2019a)
Treatment	CH_4		0.4	g/t FW	(Mertenat et al., 2019a)
	N_2O		8.6	g/t FW	(Mertenat et al., 2019a)
Product harvesting	Water	664		L	(Mertenat et al., 2019a)
	Electricity	2.93		kWh	(Mertenat et al., 2019a)
	CH_4		0.4		(Mertenat et al., 2019a)
	N_2O		8.6		(Mertenat et al., 2019a)
Residue composting and larvae refining	Electricity	0.56		kWh	(Mertenat et al., 2019a)
	Diesel	0.22		L	(Mertenat et al., 2019a)
	CH_4		630	g/t FW	(Mertenat et al., 2019a)
	N_2O		63.3	g/t FW	(Mertenat et al., 2019a)
Packaging	Electricity	1.10		kWh	(Mertenat et al., 2019a)
	Compost		150	kg	Existing
	Animal feed		350	kg	Existing

Table 2. Inventory of composting processing methods

Stage	Input Name	Input	Output	Unit	References
Conveyor machine	Food Waste	1		ton	Functional Unit
	Diesel	2.5		L	(Ouedraogo et al., 2021)
	Carbon dioxide (CO_2)		26.7	kg/t FW	(Ouedraogo et al., 2021)
	Carbon monoxide (CO)		1.469952	kg/t FW	(Ouedraogo et al., 2021)
	Nitrous oxide (NOx)		0.753419	kg/t FW	LCI dataset (Recycled Organics Unit, 2006)
	Particulate (Pm_{10})		0.008464	g/L	(Recycled Organics Unit, 2006)
	Sulfur oxide (SO_x)		2.55	g/L	(Recycled Organics Unit, 2006)
	Hydrocarbon (unspecified)		1.05	g/L	(Recycled Organics Unit, 2006)
Enumeration	Diesel	2.4		L	(Ouedraogo et al., 2021)
	Electricity	1.33		kWh/ t FW	LCI dataset (Recycled Organics Unit, 2006)
	CO_2		26.7	kg/t FW	(Recycled Organics Unit, 2006)
	CO		1.469952	kg/t FW	(Recycled Organics Unit, 2006)
	NO_x		0.753419	kg/t FW	(Recycled Organics Unit, 2006)
	Pm_{10}		0.008464	g/L	(Recycled Organics Unit, 2006)
	SO_x		2.55	g/L	(Recycled Organics Unit, 2006)
Composting	Em4	2		L/t FW	Existing Condition
	Water	38.9		L	(Ula et al., 2021)
	CO		1.469952	kg/t FW	(Ula et al., 2021)
Enumeration ripe composting	Diesel	2.1		L	(Ouedraogo et al., 2021)
	CO_2		26.7	kg/t FW	(Ouedraogo et al., 2021)
	CO		1.469952	kg/t FW	(Ouedraogo et al., 2021)
	NO_x		0.753419	kg/t FW	LCI dataset (Recycled Organics Unit, 2006)
	Pm_{10}		0.008464	g/L	(Recycled Organics Unit, 2006)
	SO_x		2.55	g/L	(Recycled Organics Unit, 2006)
Packaging	Electricity	25		kWh/ t FW	(Recycled Organics Unit, 2006)
	Compost production		500	kg	Existing

RESULTS AND DISCUSSION

Environmental impact assessment

In conducting the Environmental Impact Assessment for the BSF larvae-based waste management system, a thorough examination of various environmental impact categories is imperative. Among these, the assessment scrutinizes Human Toxicity, global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP) to ascertain the broader sustainability implications of the BSF larvae's waste conversion process. The evaluation of Human Toxicity focuses on potential health impacts, considering the presence of harmful substances in the waste and assessing exposure risks throughout the system's life cycle. GWP assessment quantifies greenhouse gas emissions associated with the entire process, shedding light on the system's contribution to climate change. EP and AP assessments delve into nutrient runoff and acidic substance release, respectively, aiming to minimize adverse effects on water bodies, soil, and ecosystems (Figure 6).

A comparison of the environmental effect is provided in Figure 7 for the Black Soldier Fly-based food waste treatment system and traditional composting. The graph illustrates four LCA impact categories which include GWP alongside acidification potential (AP) and Eutrophication Potential (EP) and human toxicity (HT). Each value reflects the LCA analysis findings for one metric ton of food waste based on combined primary data from

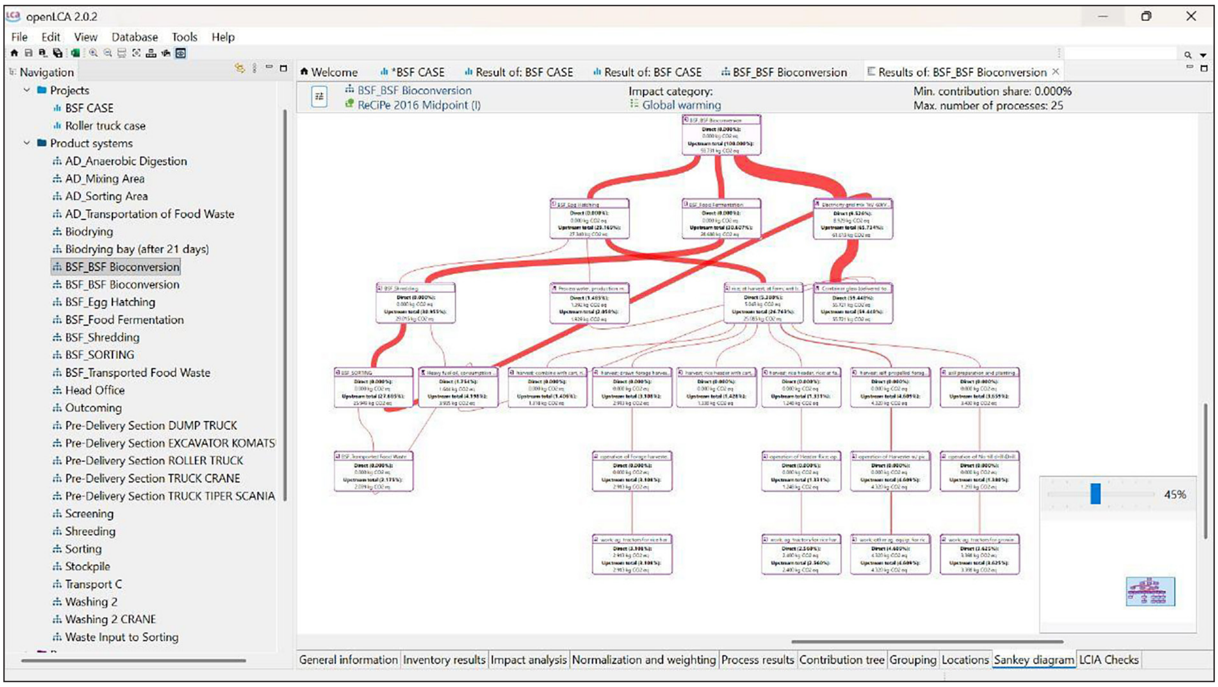

Figure 6. OpenLCA calculation process used to generate the numerical results

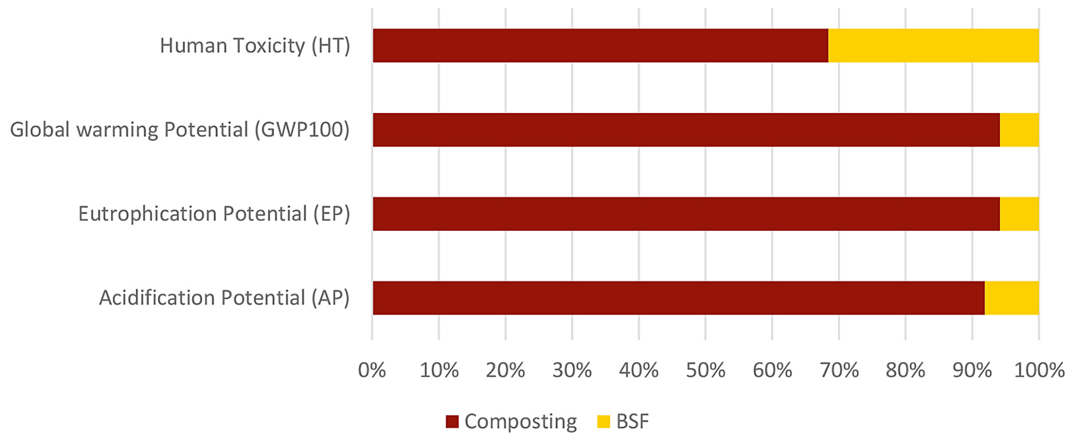

Figure 7. Impact assessment alternative

current BSF trials and secondary literature and database information about the composting process. The horizontal axis represents the analyzed impacts while the vertical axis demonstrates how much each approach contributes to these impacts. The existing figure supports the finding that the BSF approach delivers minimized environmental effects throughout all evaluated aspects when compared against traditional composting.

Global warming potential impact

The life cycle analysis revealed that the BSF based food waste treatment system had a lower GWP than conventional composting techniques. The GWP of the BSF-based system was 3.061E+01 kg CO_2 equivalent per ton of food waste treated, whereas the GWP of composting is 4.903E+02 kg CO_2 equivalent per ton of waste treated. The reduction in methane emissions is one of the primary factors for the lower GWP of a BSF-based system. The process of composting involves the aerobic breakdown of organic waste; however, methane can still be generated, albeit in smaller quantities, under certain conditions where oxygen is limited or absent, leading to anaerobic conditions (Fan et al., 2023). Methane, a potent greenhouse gas with a considerably higher warming potential than carbon dioxide, may be produced during composting if pockets of anaerobic microenvironments develop within the compost pile. This can occur when the composting material is densely packed, impeding oxygen flow to certain areas (Khandelwal et al., 2019). The limited oxygen availability prompts specific microorganisms to shift to anaerobic metabolism, resulting in the production of methane as a byproduct. While composting is generally an aerobic process, understanding and managing factors that might lead to anaerobic conditions are essential to minimize methane emissions and enhance the overall environmental benefits of composting. In contrast, BSF larvae consume organic waste aerobically, thereby reducing methane emissions during waste conversion. Energy is required for the processing, turning, and maintenance of waste in composting facilities. The consumption of energy by these facilities may indirectly contribute to greenhouse gas emissions. In contrast, the energy requirements for rearing BSF larvae are relatively low, as the larvae can convert refuse into biomass with minimal additional input.

Although both composting and BSF larval rearing produce organic-rich residues (compost and frass, respectively) that can be applied to soils, frass may have a greater capacity for carbon sequestration. Frass produced during BSF larval feeding trials functions as a biofertilizer and contributes to soil health improvement. The organic carbon in frass is sequestered in the soil, effectively removing it from the atmosphere, which can help mitigate a portion of the emissions caused by sewage treatment.

Eutrophication potential

LCA revealed that BSF-based food waste treatment systems have a lower potential for eutrophication than conventional composting techniques. The eutrophication potential of a BSF-based system is 1.262E-02 kg PO_4^{-3} eq/t food waste, whereas the eutrophication potential of composting is 2.033E-01 kg phosphate equivalent per ton of treated waste. If compare BSF and composting for food waste treatment system. BSF has the ability to help conserve water bodies and aquatic ecosystems since it has a lower EP. In practice, however, the direct impact of both methodologies on EP is negligible, as evidenced by the comparatively low EP values of both approaches. In the context of environmental concerns, these extremely low values indicate that the contribution of both methods to nutrient enhancement and eutrophication potential is negligible and can be disregarded. This is the result of nutrient discharge into the environment being minimized through the implementation of waste management practices, including judicious location and effective contamination prevention measures. The prospective impact on eutrophication is therefore likely to be minimal and can be deemed inconsequential given the current circumstances.

Human toxicity

According to the results of the life cycle analysis, the BSF-based food waste treatment system is safer for human consumption than conventional composting. In comparison to composting, which had a greater human toxicity potential of 6.64E+00 kg,-dichlorobenzene equivalents per ton of treated waste, the total human toxicity potential linked with the BSF-based system was 3.063+00 kg 1,4-dichlorobenzene equivalents per ton of treated food waste.

The potential for human toxicity is affected by the hazardous material emissions that occur during the waste treatment process. Volatile organic compounds (VOCs) and other dangerous air pollutants may be released during composting, putting people at risk for exposure and other health problems. In contrast, the process of cultivating BSF larvae does not involve high-temperature composting, and the larvae feed directly on organic waste without emitting significant quantities of hazardous compounds.

Leachate can be produced during the composting process, particularly in larger composting facilities, and it may contain traces of toxic substances. This leachate may contaminate soil and water sources, posing hazards to human health. In the BSF-based system, the larval rearing process retains the majority of nutrients and organic matter within the closed-loop system, thereby minimizing the likelihood of leachate formation and subsequent contamination.

Composting may necessitate the inclusion of bulking agents or other substances in order to optimize the process (EM4). If not correctly managed, these inputs may introduce chemical substances that pose risks to human health. With the BSF-based system, there is less chance of contaminating the environment because the larvae naturally devour organic waste without the need for additional chemical inputs. Due to worker exposure to dust, endotoxins, and microbes during waste processing, composting plants may pose risks to them. By supplying a more regulated and restricted environment for larvae development, the BSF-based system may be able to lower the dangers of occupational exposure.

The BSF-based food waste treatment system's decreased human toxicity potential suggests that it has the ability to reduce the hazards to human health posed by waste management procedures. The BSF-based system is consistent with the purpose of safeguarding human health and safety since it reduces emissions of harmful compounds, reduces the production of leachate, and eliminates the need for chemical inputs.

Acidification potential

When compared to standard composting practices, the BSF-based food waste treatment system showed significantly less acidification potential. The BSF-based system had an acidification potential of 7.365E-02 kg SO_2 equivalents per ton of treated food waste, while composting had an acidification potential of 8.333E-01 kg SO_2 equivalents per ton of waste treated, which is significantly higher.

Emissions of ammonia (NH_3) during waste treatment significantly impact the potential for acidification. Composting food scraps can result in the release of ammonia, which contributes to acidification. In the BSF-based system, the rearing of larvae serves to retain nitrogen in the closed-loop system, thereby reducing ammonia emissions. A sizable percentage of the nitrogen from the waste is present in the frass created during the larvae feeding experiments, which can be progressively released and used as a nutrition source in agriculture.

During waste processing, composting facilities can emit corrosive gases such as SO_2, particularly if large-scale composting operations involve incomplete combustion. The rearing process in the BSF-based system does not involve combustion, thereby reducing the potential for SO_2 emissions.

To reduce acidification potential, proper nutrient management is crucial. In a BSF-based system, the use of nutrient-rich frass as a bio-fertilizer enables more precise nutrient application, which can help optimize soil pH and reduce the risk of acidification.

Economy analysis

In terms of operating efficiency, the BSF-based system demonstrated a cost benefit. In comparison to composting, the BSF larvae's better waste treatment efficiency led to shorter processing durations and lower waste volumes, which in turn resulted in lower total operating costs per ton of garbage processed. The LCC analysis revealed that the BSF for food waste treatment system was more cost-effective than conventional composting techniques. Composting has a higher LCC, namely 2541.82 USD, taking into account monthly investment and operational costs of 1876.65 USD and 664.96 USD for each ton of food waste processed. Meanwhile, the BSF method has an LCC of 1785.21 USD with investment and operational costs of 1169.98 USD and 614.23 USD. The efficacy of the waste treatment methods in converting organic waste into useful products determines their cost-effectiveness (Sharmila et al., 2022). Higher conversion rates of organic waste by BSF larvae contributed to reduce per-ton processing costs (Santoso et al., 2023).

Moreover, investment in BSF and windrow composting waste management methods, you don't need to calculate the infrastructure needed in this case (land area, building costs, etc.) but what equipment is used to manage food waste. This is in line with the integration of LCA and LCC methods which must be in line with the boundaries system used, in this case gate-to-gate. In order to provide a more significant understanding of the relationship between environmental impacts and costs at the processing stage.

To optimize the composting process, composting requires additional feedstock materials (EM4), such as bulking agents and heavy equipment. The BSF-based system, largely uses organic waste as feedstock, which minimizes the need for extra resources and associated costs. The BSF-based system offers revenue generation opportunities through the sale of BSF larvae as animal feed and frass as a biofertilizer. The entire expenses of the waste treatment procedure may be partly covered by these income sources, thereby making the BSF-based system economically feasible.

A key factor in establishing the system's economic success is the value of the by-products produced during waste treatment. The utility of the frass generated by BSF larvae growing as a nutrient-rich bio-fertilizer has been established.

The potential marketability of frass as a product may drastically lower the total cost of the BSF-based system's life cycle. Economies of scale may have an impact on the LCC of both waste treatment technologies. Due to improved resource utilization and increased processing efficiency, there may be potential cost savings as the size of waste treatment operations grows. It is possible to develop cost optimization techniques for both composting and the BSF-based system by doing further investigation of cost variance at various operational scales.

Compared to composting, the BSF-based food waste management system is economically competitive due to its favorable life cycle cost. The BSF-based system's improved waste treatment efficiency, cheaper feedstock and operating costs, and potential for income generation from valuable by-products are what make it cost-effective. For detailed costs, explain in the subsection below, and the results of the comparison are shown in Figure 5.

Figure 8 presents a comparison of the total LCC between the BSF-based food waste treatment system and the conventional composting method. This graph shows the main cost components calculated per 1 ton of food waste, including initial investment costs, operational costs, additional material costs (such as EM4 in composting), fuel and electricity consumption, labor costs, and potential income from end products (larvae, frass, and compost). Cost values were calculated from primary data related to equipment use and field operations, as well as secondary data from market prices and supporting literature. The cost categories appear along the X-axis while the total cost values in US dollars appear along the Y-axis. The BSF method proves to be more cost-effective than composting because it generates higher income potential and requires lower total expenses.

Investment cost

The composting management method is carried out using the windrow composting method with a waste chopping machine that processes the crushed food waste and then continues to the next stage using a conveyor machine. The material used in the composting management method is EM4 which is used to help the composting process, electricity and diesel are used. for each machine, the composting method operator, and the profits obtained from the final product in the form of compost. Meanwhile, investment calculations include BSF cages, lights used to help the nursery process, ceiling fans to exchange air in the room so that the room doesn't have odor problems, to manage food waste food waste management areas in the form of baskets and larvae filtering equipment and compost at the final stage.

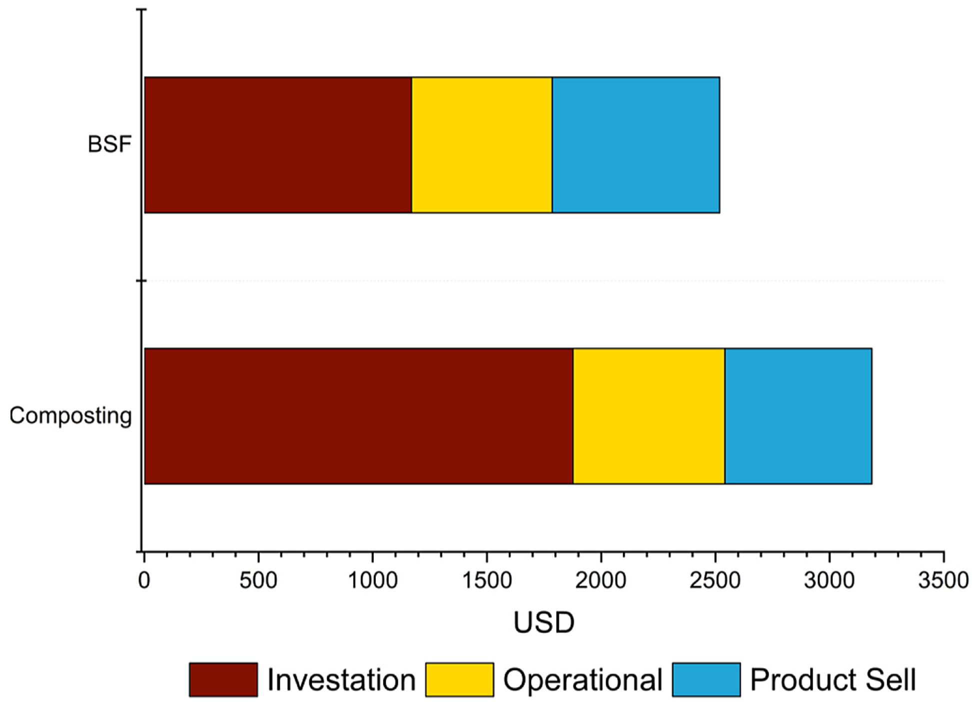

Figure 8. Life cycle cost analysis

Additional input

EM4 is commonly used in composting to accelerate the composting process and improve composting. The cost of procuring and administering EM4 was factored into the calculation of the cost of composting. However, the BSF-based system requires no additional additives, so there is no EM4 cost. Composting necessitated the utilization of EM4, which increased the overall cost. In contrast, the BSF-based system required no additional additives, which contributed to its affordability.

Diesel cost

Commonly, diesel fuel is used to power composting equipment, such as turners and waste-handling machinery. Diesel costs were factored into the composting life cycle cost computation, whereas the BSF-based system relies predominantly on electricity and does not incur diesel costs. The reliance of composting equipment on diesel fuel increased the overall cost of composting.

Water cost

Both methods of refuse treatment may require water for specific operations. Composting may necessitate water for moistening waste heaps, whereas the BSF larvae rearing facility may require water for larval maintenance. The cost of water was evaluated for both systems. Despite the fact that both systems needed water, the BSF-based system often had a lower water cost since the process of producing larvae is closed-loop, which keeps water in the system.

Electricity cost

BSF's facility for larvae rearing required electricity for illumination, temperature control, and ventilation, which contributed to the facility's electricity bill. Composting also necessitated electricity for a variety of processes, including blending and oxygenation. In general, the BSF-based system's reliance on electricity was more cost-effective, particularly in regions with inexpensive electricity rates.

Operator cost

In the life cycle cost analysis for both the BSF-based system and composting, labor expenses for waste treatment operations, such as waste management, maintenance, and monitoring, were included. Both systems required labor for refuse management, upkeep, and other tasks. Similar labor costs were incurred by both systems, which can be optimized through the implementation of effective waste treatment practices and automation.

Maintenance cost

In the life cycle cost analysis for both systems, the cost of maintaining waste treatment equipment, such as compost turners and larvae rearing equipment, was considered. Although the two systems' equipment maintenance costs were generally similar, the precise maintenance needs may change based on the kind of equipment being used and how well it is maintained.

Potential revenue

BSF larvae and composting produce valuable byproducts with substantial revenue generation potential. The results of the fresh maggot calculations can be estimated to sell up to 100% or as much as 200 kg of fresh maggots every month with a profit of up to USD 643.38. Meanwhile, the cashgot produced from the BSF process is up to 400 kg with a selling price of Rp. 35,000/kg. However, the results of cashgot sales did not show good things because the cost was relatively more expensive than the compost produced from the windrow composting method. This is in line with the analysis of profit results by (Ulya and Dewi, 2022) where sales results of only 10% of cashew products are produced from each month of harvest. Based on the results of this analysis, it is estimated that only 40 kg of cashgot is sold/month with a profit of USD 90.07. So it produces a profit of 733.45 USD. The increasing need for sustainable protein sources in the animal feed sector may be met by marketing BSF larvae as high-quality animal feed for poultry, fish, and animals. The larvae also have potential uses in the pet food business as a healthy and environmentally friendly component. As the need for aquaculture grows, BSF larvae provide new business potential as a high-quality feed for fish and shrimp. The larvae that are left behind after the meal is extracted may be turned into an organic fertilizer that has a high value in the agriculture sector. However, compost made from organic waste may be marketed as a nutrient-rich soil additive to landscapers, nurseries, and farmers. Because of its beneficial effects on soil structure and water retention, it may also be sold to amateur gardeners and horticulturalists.

The compost produced up to 500 kg from 1 ton of processed food waste is 100% sold, at a price of 1.29$/kg compost while for 500 kg compost it is up to 643.38 USD. This is in accordance with the analysis by (Jang et al., 2022) where sales are estimated to reach 11,225 kg/year or around 940 kg/month, for use in green open spaces, urban agriculture, households, ponds, ornamental plant cultivation, nurseries, green belts and landscapes. A reliable source of income for composting facilities is the waste management contracts they may get with local governments, private companies, and educational institutions. Composting enterprises may reap the benefits of incentives for removing organic waste from landfills in areas that promote landfill diversion. The economic potential of these important by-products may be maximized by exploring marketing techniques, forming partnerships, and developing dependable distribution routes. By tapping into these money-making opportunities, waste treatment facilities may implement a more eco-friendly and economically beneficial circular waste management model.

Public policy and regulation: Supporting infrastructure for implementing BFS in food waste management

The potential implementation of BSF technology to facilitate sustainable food waste management may prompt substantial reforms in public policy and regulation, ultimately resulting in the development of a resilient infrastructure to sustain this methodology. Central to this paradigm shift lies a meticulously crafted policy framework that governs sustainable waste management. The pressing necessity for central and regional governments to synchronize current regulations with the implementation of BSF technology is duly acknowledged. Non-governmental organizations, government agencies, and community groups united in recognition of the critical nature of collaboration for the accomplishment of this mission. The emergence of an institutional support network has fostered an environment that is conducive to the implementation of BSF technology. This partnership is crucial for establishing the required infrastructure and guaranteeing the efficacy of food waste management through the implementation of BSF. The implementation of BSF technology in the pursuit of sustainable waste management underscores the criticality of ensuring adherence to environmental regulations and standards. BSF utilization is regulated in accordance with stringent enforcement and monitoring mechanisms to guarantee adherence to the utmost environmental and safety criteria.

CONCLUSION

Food waste is an important global problem that continues to worsen, resulting in major environmental, social and economic impacts. This problem is especially true in Semarang, Indonesia, where accelerating urbanization and shifting consumption patterns are exacerbating the burden on waste management infrastructure. The need to adopt sustainable waste management techniques is highlighted by assessing the environmental impacts of food waste, including increased greenhouse gas emissions, land and water pollution, and loss of biodiversity. The main objective of this journal is achieved by comparing BSF-based food waste processing systems to composting. The results show that the first waste management solution has great potential as a financially viable and environmentally friendly waste management solution for the Semarang City Government. The findings show that the BSF-based approach is more beneficial for the environment than composting in terms of reducing the potential for global warming with the potential impact of 1 ton of food waste management being 3.061E+01 kg CO_2/t food waste and 4.903E+02 kg CO_2/t food waste. Moreover, lower potential for eutrophication and human toxicity, and cost competitiveness. Furthermore, in accordance with the tenets of the circular economy, the resource recovery strategy of the system transforms organic waste into valuable resources, including nutrient-rich fertiliser and animal feed. As an alternative to conventional composting, the BSF-based system is economically viable due to its potential revenue till 733.45 USD. The establishment of regulations and policies that encourage insect-based waste processing technologies should be a goal of policy makers and waste management authorities. The business world and city governments can implement a BSF-based system with the help of incentives for waste reduction and sustainable activities. Additionally, gaining public approval for BSF-based systems depends on increasing public understanding of their benefits and safety. Initiatives to educate the public can debunk myths and encourage a positive view of insect-based waste management.

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