Sustainable Household Food Waste Reduction through Black Soldier Fly Larvae Bioconversion

Mochamad Arief Budihardjo[1*], Ika Bagus Priyambada[1], Sri Sumiyati[1], Hessy Rahma Wati[2], Adora Salsa Bigita[2], Zulfikar Imampuro[2]

[1]Department of Environmental Engineering, Universitas Diponegoro, Semarang, Indonesia 50275

[2]Environmental Sustainability Research Group, Universitas Diponegoro, Semarang, Indonesia 50275

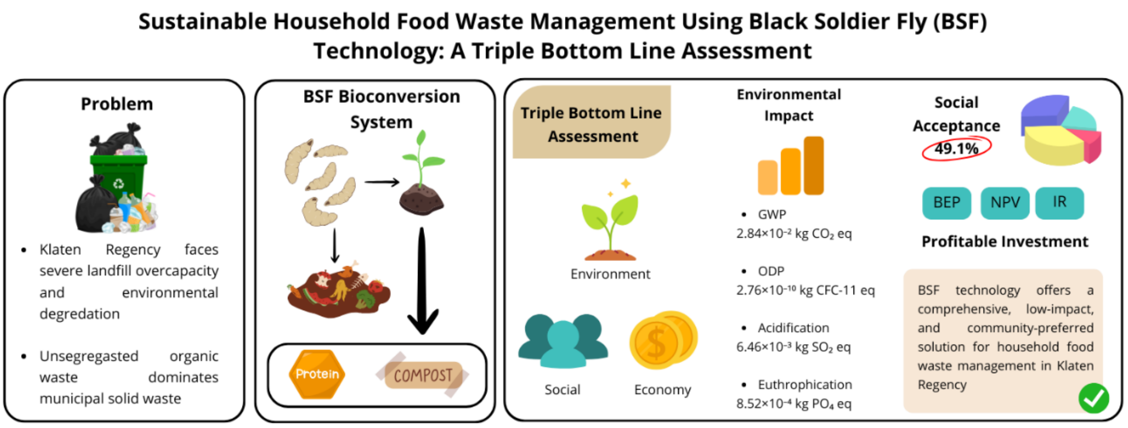
*Corresponding Author: m.budihardjo@ft.undip.ac.id

Abstract

Household food waste remains a major environmental and socio-economic issue in Klaten Regency due to the high proportion of unsegregated organic waste and limited local treatment capacity. This study assesses the implementation of Black Soldier Fly (BSF) bioconversion technology to treat household food waste through a sustainable approach which uses the Triple Bottom Line (TBL) framework for evaluation against Vermicomposting and Anaerobic Digestion systems The results show that BSF had the lowest environmental impacts, with global warming potential of 2.84×10^{-2} kg CO_2 eq, ozone depletion of 2.76×10^{-10} kg CFC-11 eq, acidification of 6.46×10^{-3} kg SO_2 eq, and eutrophication of 8.52×10^{-4} kg PO_4^{3-} eq. The economic evaluation reveals that the project will reach its breakeven point after 2.75 years while generating Rp10,995,984,094.85 in present value and delivering a 61% return on investment. Socially, BSF achieved the highest AHP preference score (49.1%), outperforming Vermicomposting (40.2%) and Anaerobic Digestion (10.7%), mainly due to lower land requirements, lower operating costs, simpler operation, and higher community acceptance. This study demonstrates that integrating TBL provides a comprehensive basis for selecting sustainable household food waste treatment technologies, with BSF emerging as the preferred option.

Keywords: black soldier fly, food waste management, sustainability, triple bottom line

Graphical abstract



1. Introduction

Food waste is a huge global environmental, economic and social issue with impact on sustainable food systems and community wellbeing. In addition to putting an additional demand on the environment, a problem like this challenges government and stakeholders with the mission of developing inclusive, feasible solutions that combine environmental preservation and food security (Aloysius et al., 2023). Research and practices on food waste control differ dramatically across developed and developing countries. These differences frequently result from improvements in public knowledge, government policies, infrastructure, and technology, all of which have an impact on local and national food waste management (Choochote & Supakata, 2025). Indonesia ranks second globally in terms of food waste production. This concerning grading highlights the urgency of targeted measures and environmentally friendly waste management techniques are needed to decrease the nation's environmental impact (Waluyo & Kharisma, 2023). In many areas, households contribute to 28.4–31.9% of the total amount of food waste, making them one of the major contributors. This demonstrates how important household-level behaviors and waste management techniques are to the entire issue of food waste (K. H. Nguyen et al., 2025; Yu & Jaenicke, 2020). Household behavioral change in food waste management is strongly shaped by individuals' perceptions of the environmental policies implemented; perceived ease of use and perceived usefulness of a green policy have been shown to foster more positive attitudes, which in turn drive both mandatory and voluntary green behavior (Yang et al., 2020). Voluntary green behavior can also spread socially through a social-learning process, in which individuals who act as role models within a household or community shape green self-efficacy and, subsequently, the green behavior of other members (Shao et al., 2023). The waste management system's current capabilities are restricted to lowering waste production. These restrictions, however, imply that in order to effectively manage the increasing amount of food waste, more sophisticated treatment technologies and holistic changes are required (Kusumaningtiar et al., 2023). Unmanaged food waste decomposes and increases greenhouse gas (GHG) emissions, affects the air, water, and land, and causes odors, thereby, affecting overall human health. This leads to a variety of negative impacts that worsen public health issues and harm environments, especially in crowded areas (Singh et al., 2022). A comprehensive unstable management strategy for developing nations such as Indonesia, a comprehensive technology assessment procedure must be established. With the use of such an assessment framework, stakeholders might completely evaluate the opportunities at their disposal and determine suitable solutions that fit the socio-economic and environmental aspects of the area (Wen et al., 2016).

Black Soldier Fly (BSF) larvae are especially an ideal as livestock feed because of their high protein content. They support the livestock industry's efforts to lessen dependency on traditional protein inputs like soy and fishmeal because of their nutritional composition, which makes them a sustainable and affordable alternative for traditional feed sources (Miranda et al., 2019). BSF larvae for biowaste recycling is an emerging technology that can convert a variety of decomposing biowastes into stable, environmental-friendly residue (similar to compost) and larval biomass, which can be used as animal feed. This creative method turns organic waste into useful resources, which not only helps with waste disposal issues but also supports the ideas of the circular economy (Mahmood et al., 2021). BSFL could encourage the breakdown of organic waste and enhance the final product's quality. The decomposition of organic matter is accelerated by the enzymatic activity and quick growth of BSF larvae, improving nutrient availability and producing higher-quality soil additions (Salam et al., 2022). Beyond post-consumption bioconversion, food waste generation can also be curbed at the preand post-harvest stages by controlling spoilage of food commodities using natural compounds. For instance, perillaldehyde, a secondary organic compound derived from perilla plants, has been shown to exert strong antifungal activity against Ceratocystis fimbriata, the main causal agent of black rot in sweet potato, by inducing fungal apoptosis through disruption of Ca^{2+} homeostasis and accumulation of Reactive Oxygen Species (ROS), thereby offering potential to extend the shelf life of food commodities and reduce household-level food waste generation (Tian et al., 2019). Maintaining a zero-waste system is one of the primary goals of many insect producers. Since almost all inputs are transformed into useful outputs, such a system seeks to maximize resource efficiency and reduce environmental footprints. The goal of zero waste efforts is to send practically barely waste to landfills by reusing and recycling as many byproducts as possible. This strategy helps greater environmental preservation efforts and appears highly compatible with sustainable waste management goals (Chavez, 2021; Romano et al., 2019). Insect production is a simpler process than other methods of bioconversion, such as Vermicomposting and Anaerobic Digestion, and can have less environmental impact as well. BSF harvesting is a desirable alternative in both rural and urban areas due to its comparatively low water consumption, reduced greenhouse gas emissions, and limited space requirement. Most BSF research focuses on industrial or large-scale agriculture. However, to fully utilize BSF technology across a range of socio-economic circumstances, it is becoming increasingly important to further studies and development at smaller, decentralized, or household levels.

As new biological processing techniques like Black Soldier Fly (BSF) bioconversion become more popular, there is a growing focus on the efficient management of food waste in homes. BSF larvae are far more effective in converting and decreasing the quantities of organic waste than traditional organic waste treatment methods like anaerobic digestion and vermicomposting. They also produce useful byproducts like insect protein and organic compost. However, choosing the best technology for a specific household or area involves a methodical evaluation of several factors, such as operational viability, environmental advantages, waste reduction effectiveness, and societal acceptance (Angelo et al., 2017). BSF, anaerobic digester, and vermicomposting solutions can be objectively assessed and prioritized using the Analytical Hierarchy Process (AHP), a strong multi-criteria decision-making framework (Chow & Abd Manaf, 2022). By using AHP, stakeholders can demonstrate the superior efficacy of BSF bioconversion over other traditional methods in the context of decentralized household food waste processing, as evidenced by its quick waste reduction rates, dual advantages of waste enhancing the value and carbon capture, and complying with the principles of the circular economy (Barry, 2004).

Limited studies have comprehensively evaluated the environmental, economic, and social performance of household-scale BSF technology while systematically comparing with other household food waste treatment alternatives. The previous study, Kusumaningtiar, Vionalita (Kusumaningtiar et al., 2023), discuss about household food waste management, but only assess the environmental impact using Life Cycle Assessment (LCA), meanwhile in Parsa, Van De Wiel (Parsa et al., 2024) using a Triple Bottom Line (TBL) method, but in urban waste management scale. In addition, recent studies have highlighted the importance of integrated waste management strategies that simultaneously enhance environmental performance, resource recovery, and long-term sustainability. For instance, He and Qu (He & Qu, 2026) demonstrated that an integrated waste management approach could reduce methane emissions by 60–70% while improving resource recovery and infrastructure resilience, meanwhile Xiao (Xiao et al., 2019) emphasized that engineering feasibility and long-term operational performance are essential considerations for the successful implementation of sustainable waste management technologies. However, these studies have not comprehensively integrated environmental, economic, and social assessments to systematically compare household-scale food waste treatment technologies within a unified decision-making framework. This limitation creates a knowledge gap in identifying the most suitable household food waste treatment technology based on comprehensive sustainability criteria. To address this gap, this study integrates the TBL, LCA, economic feasibility analysis (BEP, NPV, and IRR), and the AHP to comprehensively evaluate and compare BSF, Vermicomposting, and Anaerobic

Digestion for household food waste management. Unlike previous studies, this study provides a comprehensive sustainability assessment that combines environmental, economic, and social dimensions within a unified decision-making through integrates the TBL approach (People, Planet, Profit) in evaluating the effectiveness of BSF technology on a household-scale technology selection. In addition, an empirical comparison will be made between BSF and other household food waste treatment methods (e.g., small-scale anaerobic digesters or vermicomposting) to acquire more accurate results. Accordingly, this article aims to identify the most sustainable household food waste treatment technology by comprehensively evaluating the environmental, economic, and social performance of BSF and comparing it with Vermicomposting and Anaerobic Digestion using an integrated assessment framework.

2. Methodology

2.1 Study Area

Klaten Regency, situated in Central Java between the urban centers of Yogyakarta and Surakarta, encompasses 26 sub-districts and spans an area of approximately 701.5 km². Its diverse geography ranging from agricultural zones to urban settlements poses significant challenges in waste management as population growth drives increasing domestic waste generation. In 2022, the Troketon Landfill, the main disposal site in the region, was reported to be under pressure, receiving around 120–130 tons of waste daily and already operating at 70% of its capacity (Ratnawati et al., 2022). Current waste management systems have struggled to keep up with the volume. However, studies have indicated that a substantial portion of the waste is biodegradable and could be processed into compost, potentially extending the landfill's operational life by up to 712 days compared to scenarios without composting interventions (Ratnawati et al., 2023).

The domestic food waste treatment planning is carried out in Ceper and Karanganom Sub-District, Klaten Regency. Situated in the southernmost region of Central Java Province, Klaten Regency shares a boundary with Gunung Kidul Regency, which is part of Yogyakarta's Special Region. With a total area of 701.52 km2, Klaten Regency makes up 2.04% of Central Java.

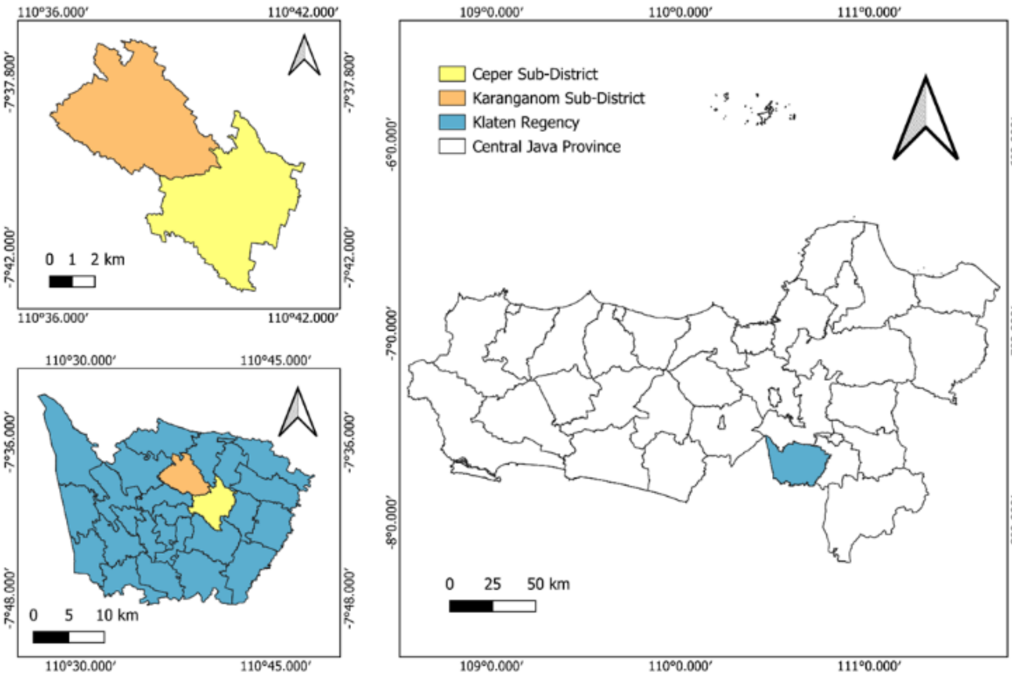


Figure 1. Study Area

2.2 Data Collection and Analysis

Primary and secondary data sources are the origins of the information. SNI 3964:1994 ("SNI 19-3964-1994," 1994), which includes sampling and computation processes is used to gather primary data through waste sampling in the research region. The Environmental Agency (DLH) and pertinent literature are the sources of secondary data, which contains details on local waste conditions and other pertinent elements. To ascertain waste component percentages, waste creation trends, and population growth rates, the gathered data is processed. The basis for determining the important dynamics in the food waste management system is provided by this analysis. A systematic evaluation framework was adopted to ensure that environmental, economic, and social parameters were consistently analyzed using standardized assessment procedures, similar to the structured evaluation methodology employed in engineering performance studies (G. Wang et al., 2025). The BSF processing systems are influenced by important factors like population increase and waste accumulation rates.

To gauge the social impact of TBL, questionnaires using AHP were used to participate in households organic waste management in Klaten Regency. A questionnaire is a set of questions posed to individuals to gather relevant information on a specific topic (Roopa & Rani, 2012). The respondents are collected using the listed criteria including personal information, environmental and waste management condition, and technical operation condition in the study area. To indicate the economic impact, including BEP, NPV, and IRR for profitable investment, Gross Regional Domestic Product (GRDP) and waste generation data are needed. Lastly, to determine the environmental impacts, it is required to collect inventory data and use LCA approach. The integration of multiple analytical methods into a unified assessment framework enables a more comprehensive evaluation of system performance, following the systematic methodology commonly adopted in engineering evaluation studies (G. Wang et al., 2025).

Other than that, observation is a method used to assess existing conditions or directly examine the planning area. The amount, composition, and processing of local household food waste can be determined through field observation (Lebersorger & Schneider, 2011; Parizeau et al., 2015). The goal is to help researchers in developing an effective waste processing system (Papargyropoulou et al., 2014). Prior to the full-scale data collection, pilot studies were carried out using a smaller selection of households. These pilot studies were conducted primarily to assess the effectiveness and clarity of the user guidance, discover any unexpected practical difficulties, and enhance the BSF technology for best household use (Lalander et al., 2013). Furthermore, to accurately assess the environmental and economic impact, a comprehensive investigation of the waste's composition and quantity was carried out (Salemdeeb et al., 2017). The proportion of food waste that was reduced could be calculated according to this measurement, which also provided data that was essential in evaluating energy consumption, emissions generated, and the resources required throughout the process and the volume of end products (maggot biomass and frass).

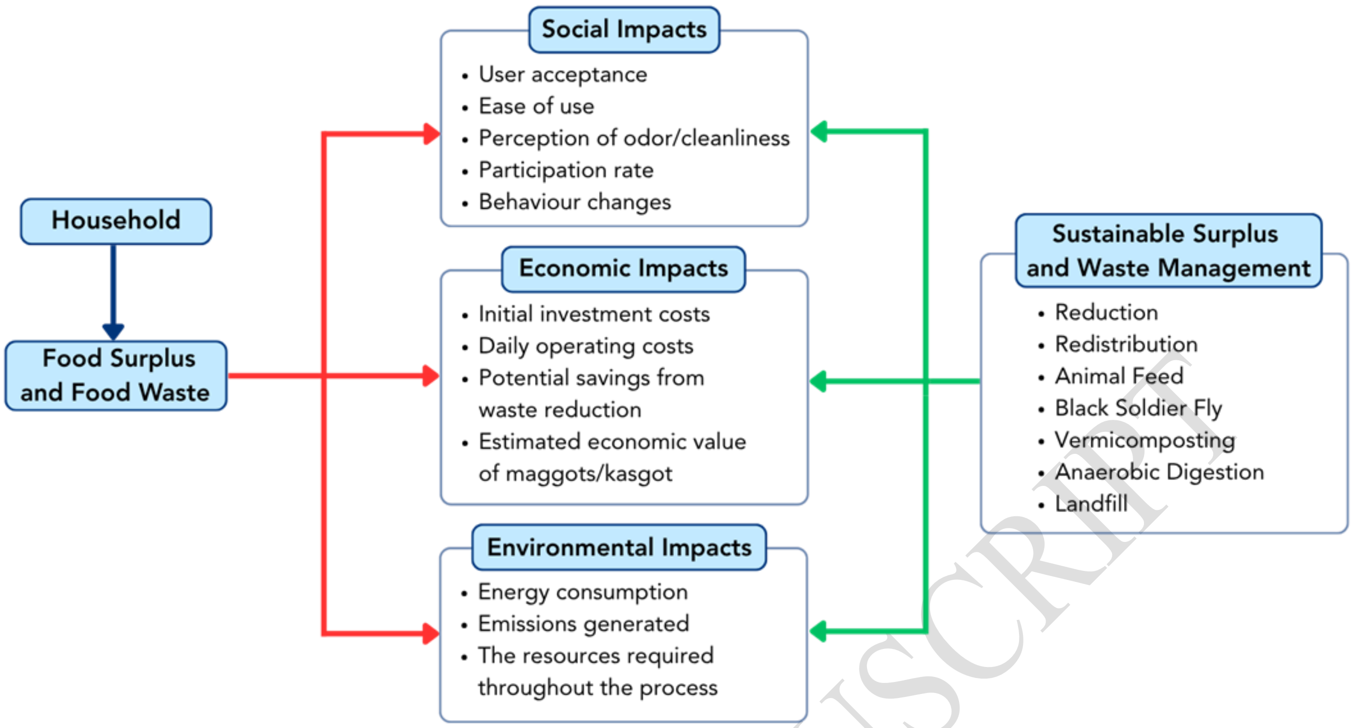


Figure 2. System Boundary Of House Food Waste Impacts Using Triple Bottom Perspective

The household is shown in Figure 2 as the primary source of food waste and surplus (Schanes et al., 2018). The earliest stage is when the following impacts emerge. In accordance with the TBL concept, the food waste and surplus then divide into three different impact categories: social, economic, and environmental. It is clear from the three red arrows that point from "Food Surplus and Food Waste" to Social, Economic and Environmental Impacts that the production of food waste and surplus directly causes or contributes to these different impact categories (Thyberg & Tonjes, 2016). They stand for the effects or repercussions that result from the first generation of food waste in the household (Jörissen et al., 2015). However, these green arrows indicate that implementing sustainable management techniques is how to reduce or minimize the negative impacts mentioned in the TBL categories. Even though they appear to be pointing upward from the effect categories, their eventual alignment into the "Sustainable Surplus and Waste Management" box implies that these effects are what make the management needed (Parsa et al., 2024). The methodological framework was designed to evaluate alternative technologies through a structured multi-criteria assessment, ensuring that each alternative was analyzed using the same evaluation procedure and performance indicators (G. Wang et al., 2025).

2.3 BSF System Overview

This study utilized a custom-designed Black Soldier Fly (BSF) bioconversion system optimized for household application in Klaten Regency, aiming for efficiency, ease of use, and minimal environmental impacts (Diener et al., 2011). The system was developed based on established BSF rearing principles and adapted to handle typical household food waste streams. Key operational stages involve a standardized pretreatment process for food waste, followed by larval processing and optimization to ensure maximum bioconversion efficiency and product quality (Barragan-Fonseca et al., 2017). The three primary parts of the BSF system are a harvesting section that effectively separates prepupae and leftover compost, a feeding chamber where pre-treated food waste is deposited, and a larval rearing unit with regulated temperature and moisture. To preserve aerobic conditions and avoid odor pollution, the system was additionally equipped with a passive ventilation structure. Compact and modular, the device was designed to facilitate decentralized waste management at the household or community level, encouraging circular resource use by producing organic residue as an addition to the soil and larval biomass for animal feed (Lalander et al., 2013). In rural-urban transition regions, the inclusion of these features was intended to encourage user participation while supporting sustainable waste management.

2.3.1 Pre-Treatment Process

To ensure optimal larval performance and consistency in the bioconversion process, all house food waste went through to a systematic pretreatment procedure to provide the best potential larval productivity and coherence through the bioconversion process (Diener et al., 2011). This phase was essential for preserving waste consistency avoiding the presence of unwanted substances and improving the larvae's capacity to perceive and absorb the base material. Clear instructions for sorting food waste at the site were given to every contributing family, with the primary focus on removing non-organic components for instance plastics, metals, glass, and excessive amounts of oil or bones (Schanes et al., 2018).

After the collected food waste was initially divided by houses, any leftover contaminants were physically removed through additional sorting. After sorting, the food waste was either manually minced or ground into shreds with a home-grade food waste grinder (T. T. Nguyen et al., 2015). Because it improved the waste's surface area while making it easier to access for microbial growth and larval being fed, this mechanical size reduction was essential (Banks et al., 2014). In addition to enabling steady feeding rates, shredding guaranteed a comparatively homogeneous substrate, reducing the possibility of anaerobic pockets or insect infestations that may result from huge, undecomposed food pieces (T. T. Nguyen et al., 2015).

2.3.2 Larval Processing and Optimization

A reliable local breeding facility provided the BSF larvae (Hermetia illucens) used in this study, assuring a steady supply of young stages (e.g., 5-day old larvae) in good condition (Diener et al., 2011). In order to enhance larval growth and bioconversion efficiency and avoid overfeeding and the ensuing anaerobic conditions, feeding rates were meticulously regulated and optimized (T. T. Nguyen et al., 2015). By giving the larvae with a steady supply of fresh substrate, this feeding schedule facilitated quick digestion and reduced the accumulation of unwanted waste (Erickson et al., 2004). If visual assessments revealed excessive residual waste or indications of prevented larval growth, adjustments were carried out (Lalander et al., 2013).

Larval health and activity in bioconversion units depend greatly on maintaining ideal environmental conditions. Temperature (preferably between 25 and 30°C), substrate moisture content (remained at 60 to 80% by cautious water addition if required, or by permitting natural moisture from food waste), and adequate airflow to guarantee aerobic conditions and avoid unpleasant odors were among the important parameters that were controlled. Given the circumstances of the household, passive methods like providing shade and making sure there was air circulation were used even though no active cooling or heating systems were used. To monitor larval behavior, substrate consistency, and to detect any early warning indicators of problems, such as the presence of pests or an excessive amount of moisture or dryness, visual inspections were carried out on a regular basis (Diener et al., 2009).

Throughout the pilot and main study phases, the bioconversion process was continuously refined based on observations and feedback. This included minor adjustments to feeding schedules, substrate moisture management, and bio-pod design to enhance the overall system efficiency and user-friendliness for households. Larvae were typically harvested when they reached the pre-pupae stage (e.g., approximately 10-14 days post-introduction, depending on the conditions), as indicated by their darker color and migration behavior (Myers et al., 2008). The resulting maggot biomass and frass (larval castings) were separated and collected for subsequent analysis, as detailed in the data collection section (Makkar et al., 2014).

2.4 Triple Bottom Line

To provide a holistic and comprehensive assessment of BSF technology for household food waste reduction, this study adopted the Triple Bottom Line (TBL) framework. TBL, encompassing social (People), environmental (Planet), and economic (Profit) dimensions, is a robust analytical tool for evaluating the true sustainability of a system, extending beyond mere financial gains. Its application in this research allowed for a multidimensional understanding of BSF's impacts, crucial for identifying truly sustainable waste management solutions in urban contexts like Klaten Regency.

The social impacts of implementing BSF technology at the household level were primarily assessed through questionnaires using AHP with participating households. Questions aimed to gauge changes in household waste management behavior, awareness of environmental issues related to food waste, and the potential for community engagement or empowerment through BSF adoption (Nadeak, 2023).

Through calculating the direct and indirect financial effects on households and the larger waste management system, financial effects were evaluated. Calculating the initial investment expenses (such as the BSF unit, starter larvae, and shredding instruments), ongoing operating costs (such as worker time and, if relevant, minimum energy), and possible financial benefits from lower waste disposal fees or fewer waste collection services were all part of this process. Furthermore, the economic value of the end-products protein-rich maggot biomass and nutrient-rich frass (compost) was estimated based on prevailing market prices for animal feed and organic fertilizers in Klaten Regency (Abro et al., 2020).

The environmental impacts were rigorously assessed by focusing on key indicators related to energy consumption, emissions generated, and the resources required throughout the process. Energy consumption for the BSF process was evaluated, considering any electricity used for shredding or minimal ventilation, and compared against the energy intensity of conventional waste collection and treatment methods. Greenhouse gas (GHG) emissions were estimated based on established emission factors for food waste decomposition, specifically comparing the potential methane emissions from landfilling an equivalent amount of waste versus the minimal emissions from BSF bioconversion (Bosch et al., 2019). Resources that required for efficiency were quantified by precisely measuring the initial weight of food waste fed into the BSF units versus the weight of residual frass and unconsumed waste.

2.5 Comparison Analysis using Analytical Hierarchy Process (AHP)

To provide more accurate and structured comparative analysis of BSF technology against alternative household food waste management methods (e.g., anaerobic digestion and vermicomposting), the Analytical Hierarchy Process (AHP) was employed. AHP is a tool that allows for the hierarchical structuring of complex problems and the quantification of relative priorities among different criteria and alternatives (Vaidya & Kumar, 2006). In this study, AHP was instrumental in systematically weighing the social, economic, and environmental criteria (derived from the TBL framework) and objectively comparing the performance of BSF against other organic waste processing technologies.

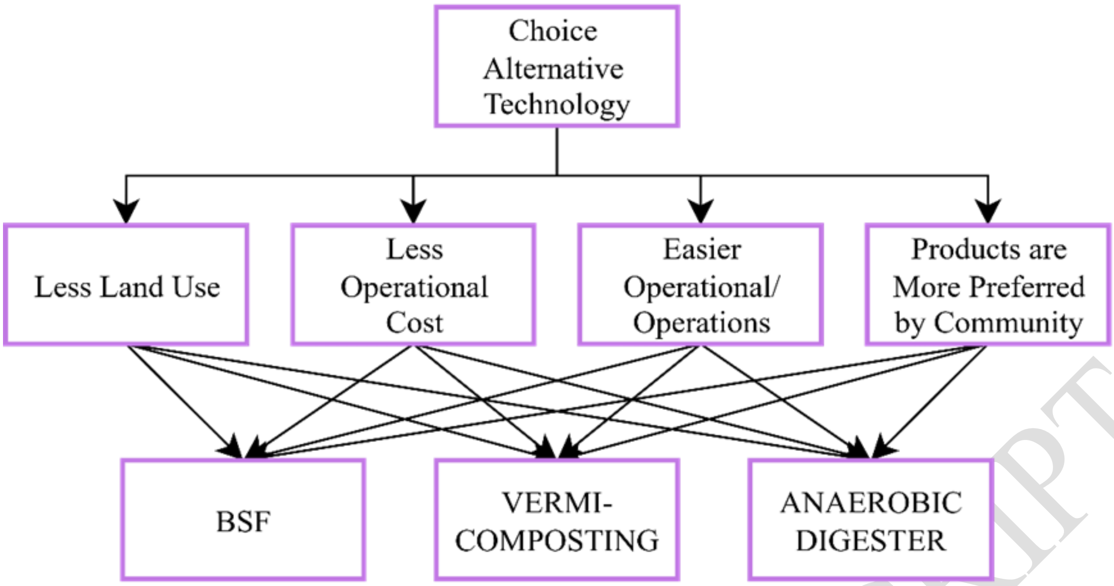


Figure 3. Hierarchy diagram of processing technology selection

The diagram that is presented in Figure 3 is a methodical framework for choosing the best alternative technology, which is especially useful in situations where environmentally friendly waste management is required. It states that the final selection of technology is dependent on achieving four important evaluation criteria: less land use, low operating cost, easier operational, and community acceptance of the final products (Handfield et al., 2002). Together, these standards provide a thorough evaluation that takes into account social, practical, economic, and environmental factors. To support a methodical and well-informed decision-making process, the framework then uses these criteria to assess certain waste treatment methods, such as anaerobic digestion, vermicomposting, and Black Soldier Fly (BSF) bioconversion.

2.6 BEP, NPV, and IRR

Net Present Value (NPV) is an analytical method to determine the difference between the business's benefits and the expenses incurred to obtain benefits (Sumbodo et al., 2022). To state in differently, NPV is used to determine if a business venture will turn a profit or a loss. A business is feasible if its net present value (NPV) is higher than zero (NPV > 0); it is in a break-even position or at the Break-Even Point (BEP) if its NPV is equal to zero (NPV = 0); and it is not feasible if its NPV is less than zero (NPV < 0) (Mahmood et al., 2021). To find NPV, the following Equation (1) can be used to determine NPV:

$$NPV = \sum_{n=1}^{y=n} \left(\frac{By-Cy}{(1+i)^y}\right) \qquad (1)$$

The NPV was determined by adding up the adjusted net advantages throughout the duration of the project. The net advantage for each year was calculated by finding the difference between the yearly benefits and the yearly expenses. The interest rate was used to consider the value of money over time, which made it possible to express future benefits and costs in terms of their present value. In this, By stands for the benefit in year y, Cy represents the cost in year y, y indicates the specific year of evaluation (y = 1, 2, 3, …, n), n is the total number of years, and i is the interest rate.

An analytical technique for determining the interest rate or discount rate is the Internal Rate of Return (IRR), which represents the net present value of the BSF maggot harvesting business when the NPV is equal to zero (Sumbodo et al., 2022). There are three criteria used in IRR, when it is feasible to run, when the break-even point is not damaging or profitable, and when it is not feasible to run. he IRR value will be higher than the interest rate when a business is profitable (IRR > Interest Rate); it is not profitable or harmful to be at the break-even point (IRR = Interest Rate); and it is not practical to operate when the IRR is lower than the interest rate (IRR < Interest Rate) (Ghandy et al., 2025). To find the IRR value, the following Equation (2) can be used**:**

$$IRR = i_1 + \frac{NPV_1}{NPV_1 + NPV_2} \times (i_2 - i_1) \qquad (2)$$

The IRR was determined by identifying a figure between two interest rates that gave both positive and negative NPV values. This approach estimates the interest rate at which the NPV goes zero, therefore showing the break-even point for the investment. A higher IRR indicates the project is more financially attractive. Here, IRR is the Internal Rate of Return; i1 is the interest rate producing a positive NPV; i2 is the interest rate connected with a negative NPV; NPV1 is the present value related to a positive NPV; and NPV2 is the present value that follows a negative NPV.

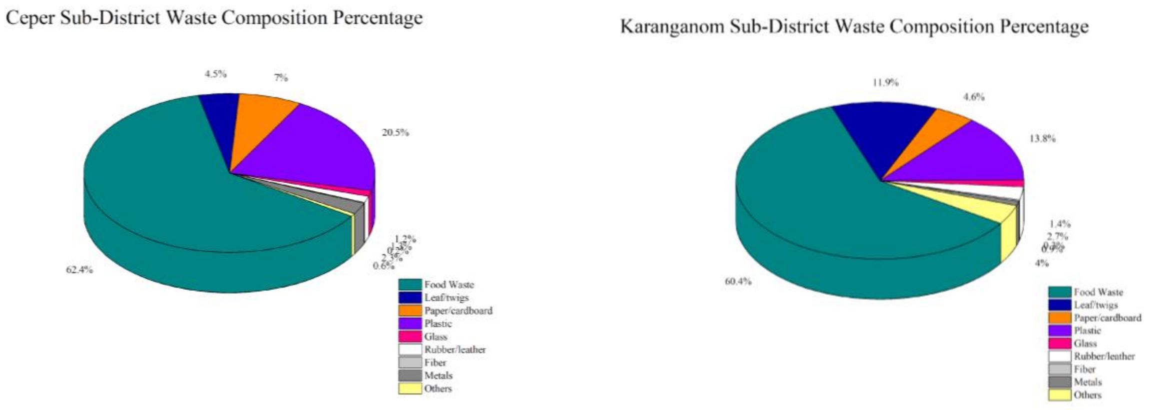
2.7 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a structured approach that could be applied to multicriteria assessments that examine on a variety of environmental issues, including eutrophication, acidification, and climate change (Larrey-Lassalle et al., 2022). Regarding the LCA models utilized in the BSFL investigations, the attributional LCA was dominant among these models. The model illustrates the energy and material flows to and from a process or product that is relevant to the environment. This makes an opportunity to compare goods that serve similar purposes (Ekvall, 2019). Conversely, consequential LCA demonstrates how important environmental flows will shift in reaction to potential choices. It includes foreseeing the long-term effects of a particular course of action. Therefore, it requires a more thorough comprehension of the economic market where the product or service is located as well as how it interacts with other production systems (Boakye-Yiadom et al., 2022).

3. Results and Discussion

3.1 Waste Composition

The waste composition was measured based on the SNI 19-3964-1994 regarding the method of collection and measurement of the samples of generation and composition of urban waste. The waste in the study area are categorized into key components: food waste, leaves and twigs, paper and cardboard, plastic, glass, rubber and leather, textiles, metal, and other miscellaneous materials. By understanding the proportions of each category, we can gain a clearer picture of the dominant waste types. The following table presents a detailed composition breakdown, which will serve as the basis for further planning and decision-making.



(a) (b)

Figure 4. Waste Composition Percentage in (a) Ceper Sub-District, (b) Karanganom Sub-District

Figure 4 presents the waste composition percentages from two sub-districts in the study area, both located in Klaten Regency. The pie charts illustrate the proportion of different waste categories, including food waste, plastics, paper/cardboard, leaf/twigs, glass, metals, rubber/leather, fiber, and others. It is clear to determine that both locations have similarity in the percentage of food waste production. Food waste in both study areas significantly exceeds the other types of waste and becomes the largest proportion of the total waste composition. This significant portion of food waste is mainly produced from domestic household sources, emphasizing the importance of focused household-level to manage organic waste in a better way for the environment.

3.2 BSF System Results

3.2.1 Performance of the BSF System During Pilot Implementation

Three alternatives, the Anaerobic Digester, Vermicomposting, and BSF (Black Soldier Fly) were evaluated in this study based on four important factors: lower operating costs, simpler operation and maintenance, reduced land use, and more community-favored products. Stakeholders can make an informed decision based on measurable evidence due to the performance analysis, which is illustrated in the supporting figures and provides a thorough comparison of how each alternative performed within these categories. The evaluation ensures that the chosen technology successfully satisfies the technical specifications as well as the community demands of the Ceper and Karanganom sub-districts by using this systematic method.

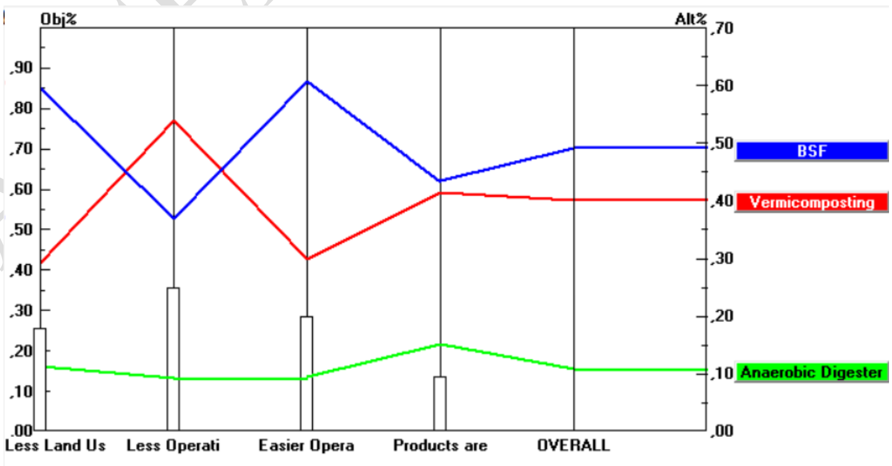


Figure 5. Performance Sensitivity for Goal: Choice Alternative Technology

Three waste management technologies, the Anaerobic Digester, Vermicomposting, and BSF are thoroughly compared in these graphical assessments, which assess each one's effectiveness against a number of operational criteria. Their relative performance is illustrated by line trajectories in the first graph, where the Anaerobic Digester consistently receives lower scores across all metrics, Vermicomposting exhibits variable performance with noticeable peaks in operational costs, and BSF shows superior results, especially in operational ease. Four main aspects are the focus of the analysis: lower operating costs, simpler operations and operations, less land use, and more preferred by community.

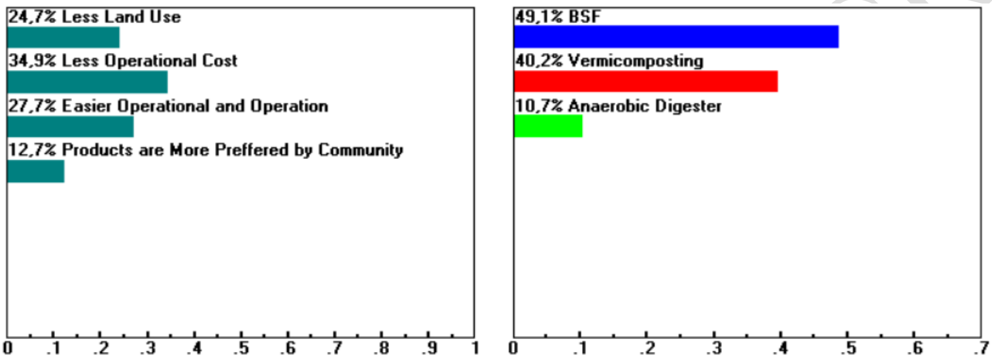


Figure 6. Dynamic Sensitivity for Goal: Choice Alternative Technology

Dynamic Sensitivity serves the accompanying percentage breakdowns, with a 34.9% reduction in operational costs, 24.7% less land use requirements, 27.7% improved operational efficiency, and 12.7% higher community preference for the resulting products. In terms of technology distribution, BSF leads with 49.1% adoption, followed by Vermicomposting at 40.2%, while Anaerobic Digester accounts for 10.7% of implementation. This distribution suggests a clear preference for BSF, which has the highest score. The strong preference for BSF observed in this study is consistent with previous findings indicating that pro-environmental behavior is strongly influenced by social norms and environmental awareness. Jiang (Jiang et al., 2022) demonstrated that individuals are more likely to adopt environmentally responsible practices when supported by favorable social and organizational contexts. Similarly, the high social acceptance of BSF in this study reflects not only its technical advantages but also its perceived environmental and practical benefits for household food waste management.

3.3 Triple Bottom Line (TBL) Impact Assessment and Product Implementation

3.3.1 Product Implementation and Community Acceptance

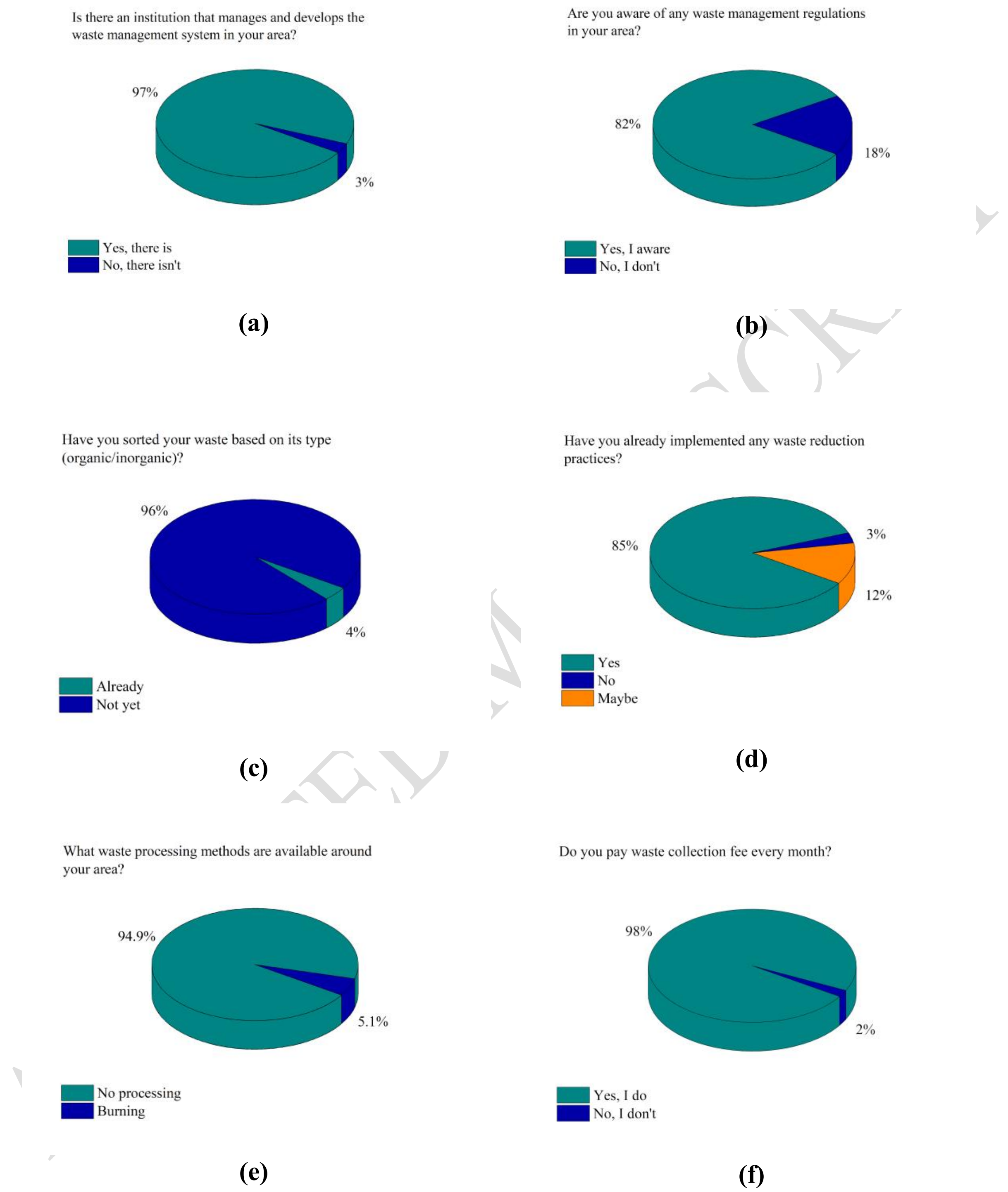


Figure 7. Questionnaire Result in Percentage (a) Waste Organization Existence, (b) Social Awareness of Waste Management Regulation, (c) Existing Waste Sorting, (d) Waste Reduction Implementation, (e) Existing Waste Processing Method, (f) Waste Retribution Payment

The research area's institutional and community environments for waste management were found to be generally supportive, according to the survey results. A vast majority of respondents (97.00%) recognized the existence of an organization in charge of overseeing and creating waste systems in their community, as seen in Figure 7 (a). This implies that Klaten Regency's waste management framework has institutional support, providing a basis for the official implementation of policies and the public distribution of programs (Aparcana, 2017). A promising degree of public awareness and possible readiness to embrace waste-related behaviors is shown by Figure 7 (b), which shows that 82.00% of respondents were aware of the waste management regulations currently in place in their area. However, without practical knowledge and systematic reinforcement, awareness might not always convert into behavior.

The amount of community engagement in basic waste management procedures is still low, despite widespread knowledge and the presence of institutions. A significant behavioral gap is highlighted by Figure 7 (c), which reveals that 96.00% of respondents had not separated their waste into organic and inorganic categories. It implies that in order to promote waste separation at the household level, policy measures or educational initiatives are required (Chen & Lee, 2020). However, Figure 7 (d) demonstrates that 85.00% of respondents reported implementing a particular kind of waste reduction, showing an optimistic trend toward sustainable behavior. Nevertheless, this data submitted by participants may include informal or inconsistent practices, and further qualitative assessment is necessary to evaluate their actual impact.

Infrastructure restrictions also appeared as a critical issue. As illustrated in Figure 7 (e), 94.9% of respondents indicated no viable waste processing techniques in their local area, while just 5.1% highlighted burning as an option. This study clearly emphasizes the necessity for decentralized and community-based processing methods, such as BSF composting systems or local material recovery facilities. Lastly, Figure 7 (f) demonstrates that 98.00% of respondents constantly pay waste disposal fees, suggesting a high level of willingness to support public services financially. This kind of behavior implies a high possibility for scaling up formal waste disposal and treatment programs provided by responsive service delivery and community involvement (Grau et al., 2022).

3.3.2 Economic Impacts

During the biotransformation process, black soldier fly larvae (BSFL) can generate two economically valuable products (Siddiqui et al., 2022). One of these products is insect protein, while the other is frass, which is rich in beneficial microorganisms, including cold-adapted species (Lopes et al., 2022). By studying economic trends and consumption behavior, it is possible to estimate the potential increase in waste and develop suitable waste management infrastructure, such as waste disposal sites. The Klaten Regency Government has made several initiatives, one of them is by optimizing the existence of the Waste Bank. In this way, waste can provide economic value for both individuals and community groups and can reduce residue disposed of in landfills.

As the economy grows, driven by increasing demand for goods and services, production and consumption levels tend to rise. This growth can result in higher waste generation. By studying economic trends and consumption behavior, it is possible to estimate the potential increase in waste and develop suitable waste management infrastructure, such as waste disposal sites.

Table 1. Business Feasibility Analysis

Investment	Rp2,332,935,999.65
IR	10.00%
BEP	2.75
NPV	Rp10,995,984,094.85
IRR	61%

The break-even point (BEP) is the time at which a business doesn't generate a profit or lose money. The BEP for this planning 3R Waste Processing Site is 2.75 years. This means that the site is expected to reach the point where its cumulative revenue equals its cumulative costs within about 2 years and 9 months of operation. Net present value (NPV) is the result of calculations that ascertain the current value of a future stream of payments using the appropriate discount rate. In general, projects with a positive net present value are considered advantageous, while those with a negative NPV are considered disadvantageous. The NPV is shown as Rp10,995,984,094.85. This is an indicator of the project's total profitability that takes the time value of money into account. A positive NPV indicates that the project is expected to generate more cash inflows than outflows when discounted to their present values, making it an economically viable investment.

The IRR (Internal Rate of Return) is listed as 61%. This represents the discount rate at which the NPV of all cash flows from the project would be equal to zero. It is a measure of the project's expected rate of return. An IRR above the required rate of return, such as the 61% shown here, suggests the project is a profitable investment. Together, these metrics - the positive cashflow, cumulative cashflow, BEP, NPV, and IRR - indicate that the 3R Waste Processing Site is a financially sound project that is expected to generate sufficient revenue to cover its costs and provide a positive return on investment for the stakeholders. These findings are also in line with Wang (B. Wang et al., 2024), who reported that biological-based approaches can simultaneously improve resource utilization while enhancing sustainability through value-added products. Although their study focused on agricultural products, it similarly highlights the potential of biological systems to maximize resource recovery and improve the overall sustainability of organic waste management. This supports the role of BSF as a circular bioeconomy solution capable of converting household food waste into valuable biomass and organic fertilizer.

3.3.3 Environmental Impacts Assessment

The comparison focuses on identifying the technology with the least environmental burden, considering key indicators such as global warming potential, stratospheric ozone depletion, eutrophication, and acidification. Among the three alternatives, one process demonstrates significantly lower environmental impacts across most categories, highlighting its potential as the most sustainable option for implementation. Table 2 below provides a summary of the total environmental impacts associated with each process, offering a clear comparison to support the selection of the most environmentally friendly technology. The successful implementation of household food waste treatment technologies also depends on appropriate operational conditions. Song (Song et al., 2026) demonstrated that system performance is strongly affected by operational stress, emphasizing that proper management practices are essential for maintaining biological process efficiency. The effectiveness of BSF bioconversion depends on more than just technological aspects because operators need to maintain appropriate waste amounts and larval population sizes and environmental conditions.

Table 2. Environmental Impact Assessment Comparison of Three Alternative Technologies

Impact category	**Unit**	**Vermicomposting**	**Anaerobic Digestion**	**BSF**
Global warming (GWP100a)	kg CO_2 eq	2.008×10^{-1}	1.491×10^{-1}	2.84×10^{-2}
Ozone layer depletion (ODP)	kg CFC^{-11} eq	1.218×10^{-9}	1.244×10^{-9}	2.76×10^{-10}
Acidification	kg SO_2 eq	3.114×10^{-2}	3.465×10^{-2}	6.46×10^{-3}
Eutrophication	kg PO_4 eq	3.833×10^{-3}	4.601×10^{-3}	8.52×10^{-4}

4. Conclusions

This research proves that the BSF bio-conversion system is the right and simple choice for treating food waste at household level of Klaten Regency. From an environmental point of view, the BSF system the BSF system plays an important role in reducing a large amount of greenhouse gases when compared with the conventional organic waste treatments. According to the Life Cycle Assessment (LCA) of the three waste treatment options, BSF showed the least environmental impact, with a total of 2.84 x 10-2 kg CO2 eq for global warming potential, 2.76 x 10-10 kg CFC-11 eq for ozone layer depletion, 6.46 x 10-3 kg SO2 eq for acidification, and 8.52 x 10-4 kg PO4 eq for eutrophication, followed by Vermicomposting and Anaerobic Digestion.

Economically, it makes possible the production of high value products, like larval mass for animal feeding and nutrient rich waste for soil enrichment, that help to close the resource cycle. Net present value (NPV) analysis shows a positive value of Rp10,995,984,094.85, which means the project is expected to provide the cumulative sum of cash more than the sum of cash outflow. Additionally, the internal rate of return (IRR) analysis shows a value of 61%, which is higher than the required rate of return, further confirming that this project represents a profitable investment opportunity.

Socially, the system encourages community participation, enhances local awareness, and fosters behavioral change toward more sustainable waste practices. Additionally, according to the AHP analysis based on four main criteria minimal land use, low operational costs, ease of operation, and community preference for the resulting products BSF was ranked the highest with a score of 49.1%, followed by Vermicomposting and then Anaerobic Digestion.

As a decentralized and suitable community intervention for sustainable food waste management, the results confirm the feasibility of BSF technology. However, BSF must be integrated into larger waste management systems at household levels to have the highest possible impact. Long-range planning, performance assessment, and policy development can also be supported strategically for the advancement of sustainable waste management schemes through using a Triple Bottom Line (TBL) assessment approach which includes environmental, economic, and social aspects. To further investigate the long-term sustainability and consistency of BSF-based systems in rural and peri-urban environments, future studies should concentrate on scalability strategies, community governance models, and Life Cycle Assessments.

Credit authorship contribution statement

Mochamad Arief Budihardjo: Conceptualization, Supervision, Project administration, Funding acquisition. **Ika Bagus Priyambada:** Methodology, Validation, Writing- Reviewing and

Editing. **Sri Sumiyati:** Resources, Data curation, Writing- Reviewing and Editing. **Hessy Rahma Wati:** Investigation, Formal analysis, Visualization, Writing- Original Draft Preparation. **Zulfikar Imampuro:** Data curation, Software, Validation. **Adora Salsa Bigita:** Investigation, Formal analysis, Writing- Original Draft Preparation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors also acknowledge the use of ChatGPT for improving readability and correcting grammatical errors, and QuillBot for paraphrasing and enhancing sentence clarity during the manuscript preparation. All AI-assisted outputs were carefully reviewed, verified, and edited by the authors, who take full responsibility for the final content of this manuscript.

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