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Sustainability Analysis of Environmental Waste Alleviation Through Bioconversion Using Black Soldier Fly Larvae: A Case Study in Depok City, Indonesia

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ABSTRACT

Depok City, Indonesia, faces significant challenges with a population of over 2 million people, substantially impacting waste issues, particularly food waste, contributing to global anthropogenic greenhouse gas emissions. To support sustainable development goals, it is crucial to reduce food loss. To address this problem, black soldier fly (*Hermetia illucens*) has emerged as a potential solution because of its ability to break down food waste into biomass. Nevertheless, environmental waste management faces challenges such as public awareness, infrastructure limitations, stakeholder engagement, and threats to long-term sustainability. This study aims to identify key leverage points for the sustainability of BSF (Black Soldier Fly) larvae utilization in waste management. The objective of this study was to identify the key sustainability factors. This study used RAPFISH (Rapid Appraisal for Fisheries) software to find the keys to sustainability. Results reveal that the sustainability status of the utilization of BSF for environmental waste management is deemed to be "Relatively Sustainable". The Department of Environmental and Cleanliness plays a pivotal role as a sustainability leverage for this program.

Introduction

Global food waste is increasing and can yield valuable components such as proteins, fats, and carbohydrates. If utilized effectively, they can help reduce greenhouse gas emissions and environmental pollution and boost the economy [1]. The proportion of the population involved in food waste at the household level is very high, with only about 6.2% showing concerns about food and environmental waste [2]. Food waste can potentially harm the environment and make a significant contribution to greenhouse gas emissions, accounting for 5% of the total greenhouse gas emissions and 6 to 18% of the total methane emissions from anthropogenic sources [3]. The food system was responsible for emissions of approximately 16 CO_2 equivalents per year in 2018, contributing to approximately one-third of the total global anthropogenic emissions [4].

In 2021, with a population of 2,085,940 people, Depok City generated 310,443 tons of waste, with the largest proportion being food waste at 62.95% [5]. The accumulation of waste over 30 m in height at the Cipayung Final Disposal Site has harmed the health of residents in the Cipayung Sub-district of Depok City [6]. Depok City, one of Indonesia's most densely populated cities, faces urban waste management challenges attributed to high and continually increasing waste production, where only 56% can be transported to landfills, primarily constrained by financial issues [7]. Depok City ranked third in West Java for the highest waste production at

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1,418.87 tons per day, predominantly household waste, with a significant portion being food waste (62.95%), plastic (21.36%), paper (6.10%), and various other materials (7.24%) [8].

Bioconversion is a method for transforming organic waste into sustainable resources BSF (Black Soldier Fly) larvae is known to be one of the ways involved in this process [9]. BSF, originating in America and adaptable to subtropical and tropical regions, has an extraordinary ability to reproduce in various organic substrates because of its high tolerance to pH changes, with BSF larvae being nutritionally rich, especially in protein content [10]. BSF larvae can reduce waste volume and support sustainable resource recovery by transforming biosolids into high-value biomass in a short period, creating the potential for a circular economy [11] and providing insights into sustainable waste reduction strategies [12]. BSF larvae can mitigate the negative impacts of food waste on the environment, while providing a sustainable protein source through the conversion of waste into biomass, which can be used as an alternative food source [13].

The BSF larvae extract has an amino acid content similar to fish meal, and its use can improve the physical and chemical quality of eggs. Meanwhile, providing live maggots as feed can reduce the fat content in the blood of laying hens [14]. BSF larvae are highly effective in processing organic waste, achieving conversion rates of 81.98% for vegetable waste, 81.23% for fruit waste, and 42.71% for garden waste, surpassing the 20% rate achieved through organic waste management without larvae [15]. The feeding of BSF larvae meal to chickens has a positive impact, with an increase in egg production by 2.60% and egg weight by 4.47% in the treatment group compared with the control group [16]. Oil and meal from BSF larvae can be used as food energy, protein, and amino acids for chicken maintenance, egg production, and yolk pigmentation. However, there may be an upper limit for food inclusion [17]. The use of BSF larvae for food waste not only provides a solution for waste management, but also generates insect biomass and organic fertilizer as valuable by-products [18], a protein source for animal feed such as livestock [19], alternative fish nutrition [20], and reduces methane emissions [21].

Sustainable development in 2030 aims to reduce food waste through upcycling to maintain nutritional value and financial benefits, while enhancing global food security and reducing environmental impact [22]. However, there are challenges in environmental waste management, including public awareness, infrastructure, stakeholder involvement, waste availability, and threats to sustainability [23]. Depok City, as a part of the metropolitan area, faces a significant issue of organic waste. To address this challenge, a design thinking approach is employed, involving stakeholders, to create more effective solutions for organic waste management [24].

Establishing long-term sustainability measures is crucial for the success of BSF larvae programs for waste management. This includes optimizing efficiency, raising public awareness, engaging stakeholders, and improving the infrastructure. Sustainable development goals emphasize the importance of reducing food waste through innovative methods, such as upcycling, which benefits the environment and global food security. Therefore, a thorough study is needed to identify key points for enhancing the sustainability of BSF larvae utilization in waste management. Integrating sustainability principles into program design and implementation is essential for the long-term effectiveness of reducing the environmental impacts of waste accumulation.

This study aimed to identify key leverage points for the sustainability of BSF larvae utilization in waste management. This study highlights the importance of integrating BSF larvae into waste management strategies to address significant challenges related to waste accumulation and environmental pollution. Cities such as Depok can develop more effective waste management systems by implementing sustainable measures, such as improving the efficiency of BSF larvae and enhancing infrastructure. These steps can strengthen community participation and support broader sustainability goals.

Materials and Methods

Study Area

The study was conducted from November 2022 to October 2023 in Depok City, Indonesia. Depok City is located at a latitude of 6°18'30"–6°28'00"S and a longitude of 106°42'30"–106°55'30"E, with a total area of 199.98 km^2. It is situated between two major rivers, namely, the Ciliwung and Cisadane River Basins [25]. This study was conducted at four BSF larvae utilization points in the Mekarjaya, Baktijaya, Cipayung Jaya, and Kukusan Sub-districts. The research location map is shown in Figure 1.

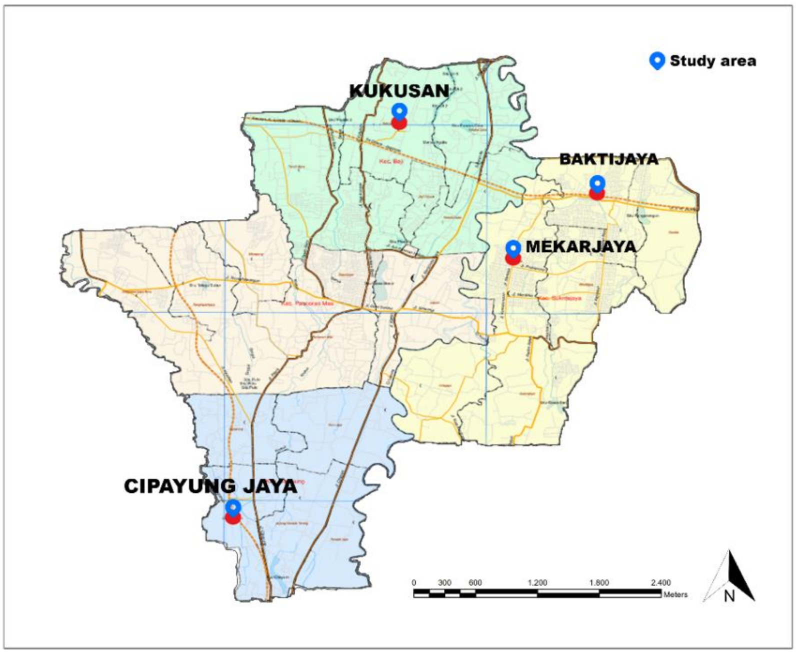

Figure 1. Study area.

Data Collection

Both primary and secondary data were used in this study. Primary data were obtained and collected directly through field observations. Data on social, economic, environmental, and governance aspects were obtained from secondary data and confirmed through the Focus Group Discussion (FGD) method involving experts and practitioners in BSF larvae utilization. Secondary data were collected through literature review of various documents from relevant institutions and previous research findings.

Data Analysis

The sustainability status of integrated waste management can be analyzed using a multidimensional scaling method. The tool employed for this methodology is RAPFISH software [26]. The stages of sustainability analysis include problem identification, determination of sustainability attributes, assessment of sustainability attributes, Monte Carlo analysis, leverage analysis, and the identification of key sustainability leverage points. Ordination analysis is carried out through several steps, including (1) determining attributes, (2) assessing each attribute using an ordinal scale (scoring) based on sustainability criteria from each dimension, (3) Using the Multidimensional Scaling (MDS) method in RAPFISH ordination analysis to determine ordination and stress values, (4) evaluating multidimensional sustainability indices and status for each dimension, and (5) conducting sensitivity analysis (Leverage Analysis) to determine the most sensitive factors influencing sustainability.

The RAPFISH analysis method employs ordination techniques with MDS, Monte Carlo analysis for the stability of ordination results, and leverage analysis to identify sensitive attributes across various dimensions to evaluate multidisciplinary sustainability [27]. Sustainability can also be measured by analyzing 5 (five) dimensions: environmental, social, economic, government, and technological aspects [28].

To assess sustainability, scores for each attribute were analyzed using Multi-Dimensional Scaling (MDS), with estimated score values for each dimension expressed on a scale ranging from 0 (worst) to 100 (best) [29]. The intervals of the sustainability indices are listed in Table 1.

Table 1. Sustainability index and its status.

No	Index	Category	Sustainability status
1	0.00 – 25.00	Bad	Unsustainable
2	25.01 – 50.00	Low	Less sustainable
3	50.01 – 75.00	Medium	Relatively sustainable
4	75.00 – 100.00	High	Highly sustainable

Source: Kavanagh and Pitcher [30].

Results and Discussion

The attributes of the sustainability analysis were obtained from literature. The attributes and sources of references are listed in Table 2. From Table 3, the average sustainability values range from 62.59 to 68.06. This indicates that the program is considered “relatively sustainable”.

Table 2. Sustainability attributes and the references for each dimension.

No	Dimension	Attributes	References
1	Environment	Land use	Tonini et al. [31]
		Water ecotoxicity	Vandermeersch et al. [32]
		Waste reduction	Chaudhary et al. [33]
		Chemical fertilizers substitution	Iacovidou and Voulvoulis [34]
		Greenhouse gas emissions	Ivic et al. [35]
		Negative Impact	Tonini et al. [31]
2	Social	Public acceptance	Pubule et al. [36]
		Social equity	Iacovidou and Voulvoulis [34]
		Odours	Tonini et al. [31]
		Job creation	Tonini et al. [31]
		High risk for employees	Ivic et al. [35]
		Noise	Iacovidou and Voulvoulis [34]
3	Economy	Cost of raw materials	Iacovidou and Voulvoulis [34]
		Investment costs	Tonini et al. [31]
		Maintenance costs	Stefanović et al. [37]
		Revenue	Stefanović et al. [37]
		Population affected or served	Achillas et al. [38]
		Revenue from byproduct	Iacovidou and Voulvoulis [34]
4	Technology	Capacity	Taelman et al. [39]
		Supporting machine/tools	
		Technical reliability	Achillas et al. [38]
		Technology maturity	Wang et al. [40]
		Energy consumption	Rodrigues et al. [41]
		Applicability	Achillas et al. [38]
5	Governance	Local community	Ivic et al. [35]
		Partnership	Ivic et al. [35]
		Supply chain	Ivic et al. [35]
		Training	Rodrigues et al. [41]
		Support from government	
		Monitoring and reporting	Kocmanová and Šimberová [42]

Table 3. Sustainability index at different locations in Depok City.

No.	Location	Environment	Social	Economy	Governance	Technology	Average
1	Cipayung Jaya Sub-district	73.10	64.85	66.88	44.37	63.75	62.59
2	Kukusan Sub-district	81.49	66.84	68.28	49.95	63.25	65.96
3	Bakti Jaya Sub-district	77.91	68.89	58.25	71.53	63.73	68.06
4	Mekar Jaya Sub-district	72.53	71.56	60.54	42.35	86.19	66.63

The BSF larvae utilization location in the Bakti Jaya Sub-district has the highest sustainability value of 68.06. In contrast, the lowest sustainability value was in the Cipayung Jaya Sub-district, which was 62.59. The lowest value is in the governance dimension of the Mekarjaya Sub-district, which is 42.35. This indicates that the governance dimension can be a leverage point for program sustainability.

Figure 2 shows the sustainability status for each dimension. The highest environmental dimension was in the BSF larvae utilization location in the Kukusan Sub-district, with a sustainability value of 81.49. Meanwhile, the location in the Mekar Jaya Sub-district had the lowest sustainability value of 72.53. This indicates that the BSF larvae utilization location in the Kukusan Sub-district can serve as a model for other areas, especially in the environmental dimension. The highest social dimension was in the BSF larvae utilization location in the Mekar Jaya Sub-district, with a sustainability value of 71.56. Meanwhile, the location in the Cipayung Jaya Sub-district had the lowest sustainability value of 64.85. This indicates that the location of BSF larvae utilization in the Mekar Jaya Sub-district can serve as a model for other areas, especially in the social dimension.

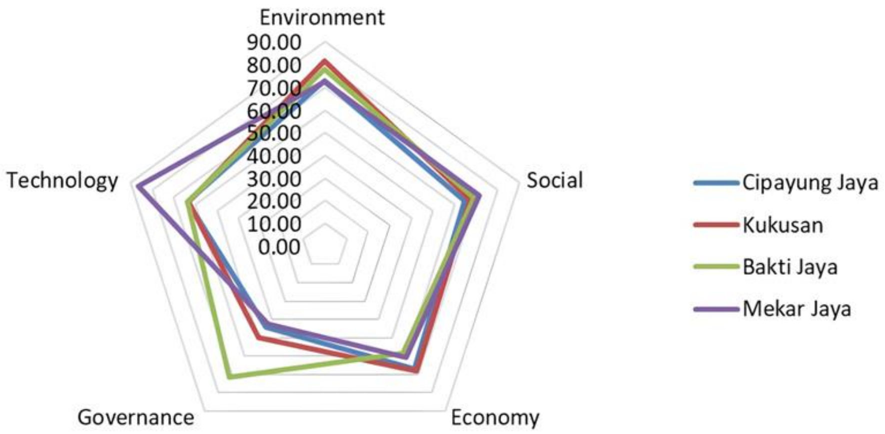

Figure 2. Sustainability kite diagram at different locations.

The highest economic dimension was in the BSF larvae utilization location in the Kukusan Sub-district, with a sustainability value of 68.28. The Bakti Jaya Sub-district has the lowest sustainability value (58.25). This indicates that the BSF larvae utilization location in Kukusan Sub-district can serve as a model for other areas, especially in the economic dimension. The highest technology dimension was in the BSF larvae utilization location in the Mekar Jaya Sub-district, with a sustainability value of 86.19. Meanwhile, the location in the Kukusan Sub-district had the lowest sustainability value (63.25). This indicates that the BSF larvae utilization location in the Mekar Jaya Sub-district can be used as a model for other areas, particularly in the technology dimension.

The highest governance dimension was in the BSF larvae utilization location in the Bakti Jaya Sub-district, with a sustainability value of 71.53. Meanwhile, the Mekar Jaya Sub-district location had the lowest sustainability value (42.35). This indicates that the location of BSF larvae utilization in the Bakti Jaya Sub-district can serve as a model for other areas, especially in the governance dimension. In particular, the governance dimension had the lowest value compared with the other dimensions, with sustainability values below 50%. This indicates that the sustainability status for the governance dimension is “less sustainable”. Therefore, the governance dimension of BSF larvae utilization needs improvement to enhance its sustainability status. The factors influencing sustainability in the governance dimensions include several key elements.

First, active involvement and support from the local community plays a critical role in ensuring the project's sustainability. Their participation spans various areas, from waste management initiatives to active engagement in socioeconomic programs linked to the project's objectives. Partnership or collaboration with external parties, including government bodies, non-governmental organizations, and private enterprises, is also essential. Such partnerships enhance a project's effectiveness and long-term viability. Moreover, maintaining a stable supply chain of raw waste materials is crucial for the continuous operation of the BSF larvae utilization project. Additionally, providing adequate training for the local community regarding waste management practices and BSF larvae cultivation techniques strengthens their capabilities and understanding, thereby bolstering the project's sustainability.

Government support in the form of regulations, permits, and technical assistance further contributes to ensuring the operational sustainability of the project. Finally, implementing effective monitoring and reporting systems enables the identification of issues, tracking progress, and measuring a project's impact. This facilitates timely corrective actions and adjustments to strategies, ensuring project sustainability in the long run. By considering and implementing these factors effectively, the likelihood of success and sustainability of the BSF larvae utilization program in Bakti Jaya and Mekar Jaya Sub-Districts can be significantly increased. The key sustainability attributes in this research for each dimension include waste reduction level (environmental dimension), provision of new jobs and odors (social dimension), economic impact on the community (economic dimension), availability of supporting machines (technological dimension), and support from government (governance dimension).

Figure 3 shows the data processing results, indicating the sustainability attributes. Regarding the environmental dimension, the attribute that can be a key leverage for sustainability is the amount of waste reduction, with a value of 7.14. This indicates that the amount of waste reduction in BSF larvae utilization has not significantly addressed the waste issue in Depok City. Therefore, attention and improvement are needed for this waste reduction attribute to increase the sustainability values. Information from the FGD results suggests that this is due, among other things, to the difficulty of each BSF larvae utilization location in obtaining waste as raw material. In addition, the effectiveness of waste management needs to be improved to increase the waste reduction rate. This can be achieved, among other things, by guiding optimal BSF larvae utilization.

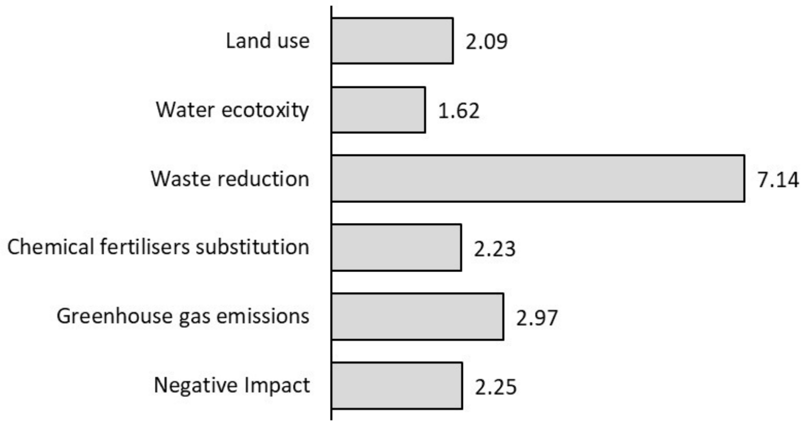

Figure 3. Environmental dimension of waste alleviation.

Waste reduction is crucial in the environmental dimension as it is the main goal of BSF larvae utilization. This aligns with several previous studies stating that one of the benefits of BSF larvae is the reduction in environmental waste. Other studies have shown that BSF larvae can reduce waste [43] and transform organic waste into biomass [44]. BSF larvae consume 200 mg of food waste per day [45] and convert it into biomass [46].

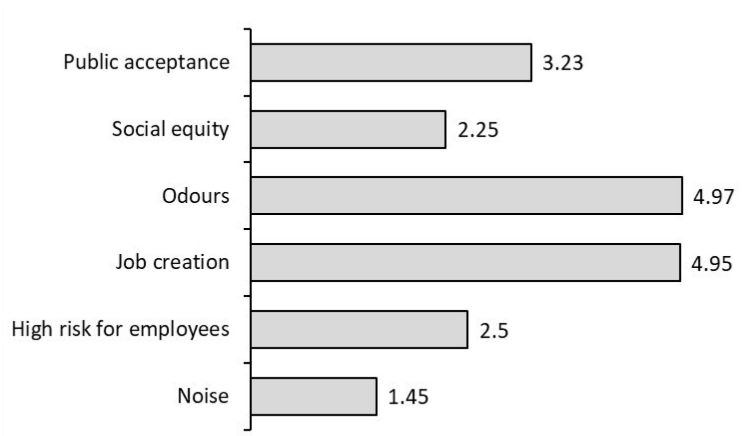

Figure 4. Social dimension of waste alleviation.

Figure 4 displays the attributes of the social dimension. Regarding social dimension, the attribute to consider is the availability of new job opportunities. The key leverage attributes for sustainability in the social dimension are new job opportunities and odours, with sustainability values of 4.95 and 4.97. This indicates that to enhance the sustainability of the social dimension, each location needs to assure the community that waste management infrastructure using BSF larvae does not produce odours, as perceived by some community members. Direct field observations showed that waste management at each location did not generate disturbing odours. One way to address this issue is to re-communicate waste management using BSF larvae to the community, addressing concerns about odours and creating new job opportunities. Therefore, government assistance is needed, especially to raise awareness among the community about the benefits of waste management using BSF larvae.

The key attributes of the social dimension are odours and the provision of new job opportunities. Odours from the BSF larvae utilization process are crucial as they affect the community's decision to grant permits to construct BSF infrastructure in the surrounding areas. Based on field surveys, the BSF infrastructure does not produce odours because BSF larvae can rapidly degrade organic waste. Concerning this, the community needs to be educated that BSF infrastructure does not create odours that will disturb the environment around their homes. Providing new job opportunities, such as serving as technical BSF operators for waste collection and maintaining the BSF cycle, can be an attraction for this program.

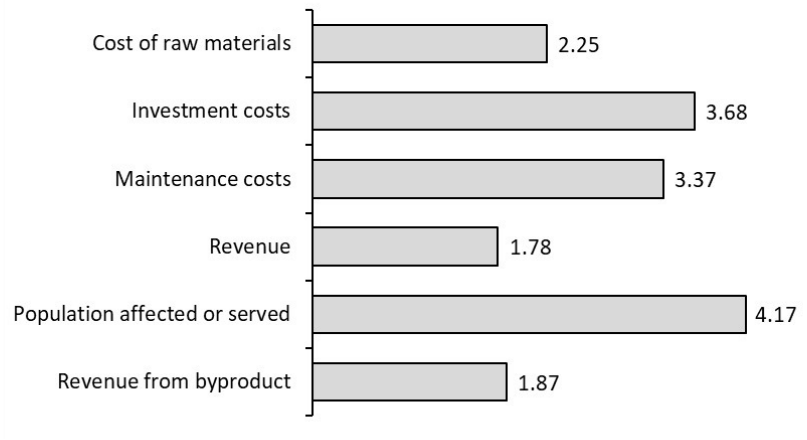

Figure 5. Economic dimension of waste alleviation.

Figure 5 illustrates the sustainability attributes of the economic dimension. For the economic dimension, the key leverage attribute for sustainability was the economic impact on the community, with a value of 4.17. This indicates that community engagement in BSF larvae utilization is more likely if they can experience economic benefits. Therefore, more rational reasons regarding waste management using BSF larvae in the community are needed, such as reducing waste collection fees or providing incentives to the community.

The key economic attribute is the economic impact on the community. For this aspect, the community needs socialization and education about the economic impact, including increased income from the sale of BSF eggs, BSF larvae, and by-products such as organic fertilizer. The market for selling BSF eggs includes other BSF operators or community members interested in implementing this program. The market for selling BSF larvae includes livestock farmers, ornamental fish breeders, and others. The market for selling organic fertilizers includes planters and plant enthusiasts in the community. This aligns with other studies indicating that cultivating BSF larvae as an alternative high-quality animal feed can create promising business opportunities. [47]. The results of other studies indicate that the majority of consumers have a positive perception of eggs from chickens fed with BSF larvae feed [48]. Other studies have revealed that feeding Nile tilapia fry with a diet of BSF larvae improved growth, feed efficiency, liver and intestinal organs, enhanced productivity, reduced feed costs by 30%, and yielded an economic return that was 4% higher [49].

Figure 6 presents the data on the sustainability attributes of the technological dimension. For the technological dimension, the attribute that can be a key leverage for sustainability is the availability of supporting tools. The supporting tools in question include waste shredding machines, temperature-measuring devices, and humidity-measuring devices to enhance the performance of BSF larvae in the bioconversion process. It would be even better if IoT (Internet of Things) is utilized to monitor the actual performance of BSF larvae. The key attribute of the technological dimension is the availability of supporting tools such as waste shredding machines. A waste shredding machine is crucial for effective and efficient operation of the bioconversion process. This aligns with previous research stating that the bioconversion process using BSF larvae as biodegradation agents can transform up to 84% of market organic waste when shredded and 69% of non-shredded waste [50].

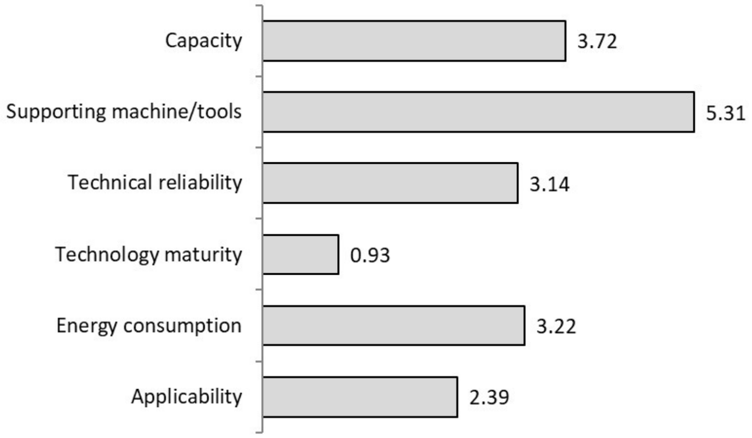

Figure 6. Technology dimension of waste alleviation.

Figure 7 displays the sustainability attributes, particularly in terms of governance. One attribute requiring attention is government support. Government support in this case came from the Department of Environmental and Cleanliness, the agency responsible for waste management in Depok City. During the study period, government support included financial and technical expertise. Financial aid can support the implementation of waste management by using BSF larvae. Government agencies also offer technical expertise and guidance to project stakeholders, providing insights into best practices, technology adoption, and operational optimization. As shown in the data above, the governance dimension is the lowest among the dimensions with a status of “less sustainable”. Therefore, the governance dimension needs more attention, as it is a key dimension for a program's success. Figure 6 indicates that the key leverage attributes for sustainability are support from the government, availability of waste raw materials, and involvement of the local community.

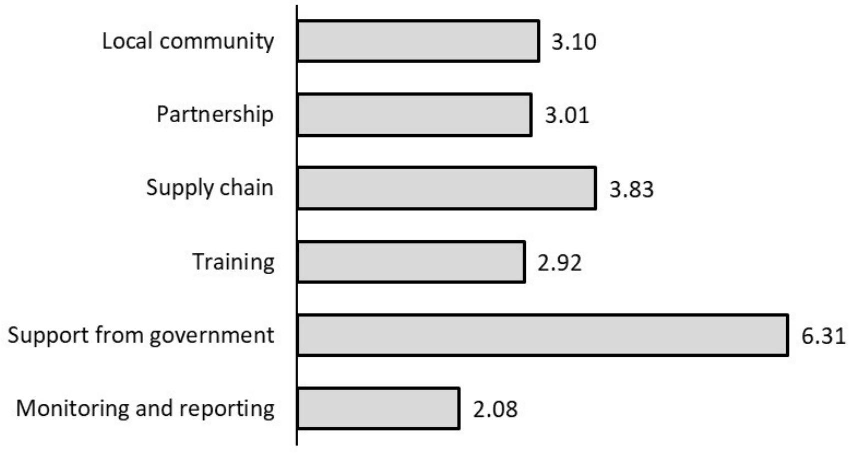

Figure 7. Governance dimension of waste alleviation.

Among the five measured sustainability dimensions, governance was the key dimension for the sustainability of this program. Attributes of the governance dimension include support from the government, availability of waste raw materials, involvement of the local community, collaboration with various parties, training, and monitoring and reporting. Government support is crucial in waste management using BSF larvae, including accompanying BSF operators to optimally implement the program, conducting public awareness campaigns to encourage community involvement, and actively involving entrepreneurs to support the program. This research is aligned with the responsibilities of the government, which covers environmental issues, including policy formulation, technical implementation, administration, monitoring, and evaluation. The results of this research are also consistent with those of previous studies, indicating that one of the key sustainability factors for waste programs is stimulation and facilitation by local governments [51]. Another study states that the limited number of field officers in the DLHK (*Dinas Lingkungan Hidup dan Kebersihan*) and the need for more consistency in conducting socialization are two factors hindering the effectiveness of the Zero Waste City program implementation [8].

The second attribute of the governance dimension was the availability of raw waste materials. The availability of raw materials, particularly waste, requires further attention. In this case, the city government and the Department of Environmental and Cleanliness can coordinate with the Department of Youth, Sports, Culture, and Tourism to collaborate with entrepreneurs in managing waste generated by hotels, restaurants, and cafes. The Department of Environmental and Cleanliness can also collaborate with the Department of Trade and Industry and the Market Management Unit to provide raw waste materials, especially from markets. Based on the field survey, BSF managers independently and proactively obtained organic waste from various sources such as restaurants, markets, and households. Although free, BSF operators must expend efforts to collect waste from their sources. In the future, it would be better if BSF operators only collected waste from Temporary Collection Points.

The third attribute of the governance dimension was the involvement of the local community. The involvement of the local community is also crucial, including youth organizations, family welfare empowerment, and community empowerment institutions, to actively participate in this program. This aligns with previous research on strategies to address waste issues, including awareness campaigns, environmental monitoring, training, and education [52], involving the community, communicating with the DLHK [24], and education and mentoring [53]. Education on the cultivation of BSF larvae as an alternative high-quality animal feed to address the issue of rising animal feed prices, increase poultry and fish production, and create solutions for household organic waste management and promising business opportunities [47].

The fourth attribute of the governance dimension is collaboration between various parties. The Department of Environmental and Cleanliness needs to coordinate and facilitate BSF operators to collaborate with companies to channel Corporate Social Responsibility (CSR) for this program. CSR funds can be allocated to finance infrastructure development or to support the operational aspects of BSF larvae utilization in Depok. This aligns with previous research stating that waste management infrastructure is needed in Depok, including the provision of maggot cultivation facilities in each neighborhood [54], improving awareness of waste separation, and seeking alternative funding sources to support waste management operations in the area [55].

The fifth attribute of the governance dimension was training. Training is crucial for both BSF operators and the community to ensure the effective implementation of BSF larvae utilization. This aligns with previous research that highlights strategies to reduce waste, including socialization, environmental monitoring, training, and education [52]. The sixth attribute of the governance dimension is monitoring and reporting. This process is also crucial for continuously evaluating the BSF larvae utilization process to seek improvement.

In this study, the sustainability evaluation of the BSF larvae utilization program for waste management in various sub-districts of Depok City yielded findings that provide a comprehensive overview of the program's performance, indicating that it is "relatively sustainable". Through an analysis of sustainability attributes, it is evident that waste reduction, public acceptance, economic impact, availability of technological support tools, and government support are key factors in maintaining the sustainability of the program. These results emphasize the importance of an integrated approach involving active community participation, collaboration with the government, and technological optimization to achieve better sustainability. Additionally, it is crucial to strengthen the governance dimension, particularly through increased government support, community engagement, and training as strategic measures to enhance the sustainability of the BSF larvae program.

Conclusions

Overall, using BSF larvae for environmental waste management is deemed "relatively sustainable". The key leverage points for the sustainability of this program lie in the governance dimension, especially the support from the Government (Department of Environmental and Cleanliness). For future research, it is recommended to investigate the involvement of various stakeholders in the success of this program.

Author Contributions

SZ, AJ, BNP, MRF: Conception and design of the study; **SZ, TT**: Acquisition of data; **SZ, TT**: Analysis and/or interpretation of data, **SZ, AJ**: Drafting the manuscript, and **AJ, BNP, MRF**: Critical review/revision.

Conflicts of interest

There are no conflicts to declare.

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