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Original Research Article

Sustainability Analysis of Black Soldier Fly Cultivation in Mojokerto City using Multidimensional Scaling-Rapfish

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Abstract

Urban organic waste remains a major environmental challenge in developing cities worldwide. It constitutes the bulk of municipal waste streams, primarily the organic fraction, including household food waste and organic market scraps, and contributes significantly to greenhouse gas emissions. BSF larvae bioconversion offers a nature-based solution that can reduce organic waste while producing valuable biomass for circular bioresource systems. However, research that quantitatively evaluates the multidimensional sustainability of community-based BSF cultivation programs at the city level, particularly in Indonesia, is limited. This study evaluated the sustainability of the BSF cultivation program in Mojokerto City using MDS-RAPFISH, which encompasses five dimensions: environmental, economic, social, institutional, and technological. An indicator-based assessment utilizing conceptual modelling and policy analysis determined the program's sustainability status and leverage attributes. The overall sustainability index was 54.22, which indicates moderate sustainability. The highest score was recorded in the environmental dimension (74.97). The subsequent dimensions were social (66.34), institutional (65.82), technological (61.70), and economic (60.92). These results show that there are constraints in terms of community participation, institutional support, technological consistency and market integration. The results show that although BSF cultivation has significant environmental benefits, it needs to be supported more technically and economically to be sustainable.

Keywords: BSF; maggots; multidimensional scaling; organic waste; sustainability analysis; waste management

1. Introduction

Urban waste disposal is regarded as a major environmental and governmental challenge in fast-growing cities worldwide. In many Southeast Asian countries, including Indonesia, organic waste constitutes the largest fraction of municipal solid waste and contributes substantially to greenhouse gas (GHG) emissions, leachate generation, disease vector proliferation, and overall environmental deterioration in many urban areas (Anokye, 2025; Mertenat et al., 2019). Failure to manage organic waste effectively can lead to water and soil contamination due to the decomposition process, which produces toxic substances such as methane and ammonia(Kurniawati and Ali, 2024). Improved organic waste management is crucial not only for environmental protection but also for fulfilling climate change mitigation commitments under the Sustainable Development Goals (SDGs) and the Paris Agreement(Jami et al., 2025). According to extant research, the majority of anthropogenic methane emissions are attributable to methane released by the anaerobic decomposition of organic waste. Therefore, proper waste management is necessary to reduce these emissions and limit global warming (Anokye, 2025; Diener et al., 2011b). Although national-level political initiatives aimed at boosting waste reduction at the source are becoming increasingly common, many local governments continue to dispose of waste in landfills. This practice is unsustainable given the growth of urban populations and the approaching critical capacity limits of landfills (Anokye, 2025; Diener et al., 2011b).

Biological approaches to organic waste treatment, particularly bioconversion using BSF larvae, have garnered significant global attention for alleviating these systemic problems. The city of Mojokerto has implemented Black Soldier Fly (BSF) cultivation as part of its organic waste management program, as the majority of the city's waste consists of household organic waste and waste from traditional markets. According to a 2023 study on waste identification and generation in Mojokerto City, food waste accounted for the largest portion of household waste (53.85%). This indicates an abundant supply of organic waste as raw material for BSF larvae cultivation. In Mojokerto City, the solid waste management system primarily focuses on collection and disposal. Source-separated waste collection remains limited, resulting in a high reliance on landfill disposal. This has led to an increased burden on landfills. Ineffective management of organic waste poses a risk of environmental pollution. The watery and easily decomposable nature of organic waste presents a challenge for conventional disposal. Therefore, appropriate and effective management strategies are needed, one of which is the use of biological treatment approaches, such as the cultivation of black soldier fly larvae (BSFL). BSFL cultivation systems offer several advantages, including high waste reduction efficiency, rapid bioconversion rates, and the production of valuable biomass that can be utilized as protein-rich livestock feed or soil amendments (Barragán-Fonseca et al., 2017; Camperio et al., 2025; Singh et al., 2021). As a nature-based solution, BSFL bioconversion aligns with the principles of a circular economy by transforming organic waste into an economically valuable resource while reducing environmental burdens (Gold et al., 2018; Surendra et al., 2016). Although many studies have highlighted the potential of BSFL to support sustainable waste management, empirical evidence regarding the sustainability performance of community-scale BSFL initiatives within an urban governance framework is limited (Ferronato et al., 2024; Rehman et al., 2022; Tariq et al., 2025).

Such initiatives can be explored with the Mojokerto City of East Java Province, Indonesia, as a relevant case to investigate. A Black soldier fly larvae (BSFL) cultivation program is required for Mojokerto City, as domestic waste in Mojokerto City is growing every year and has limited landfill capacity and insufficient urban waste management infrastructure. Due to the limited capacity to manage organic waste, these problems are expected to worsen, ultimately leading to a decline in environmental quality and negative health effects. The Black Soldier Fly larvae (BSFL) cultivation program was initiated to alleviate the waste management burden and facilitate the city's evolution towards a more sustainable, recycling-based waste disposal approach. In the same neighborhood, which is generating an increasing amount of organic waste, mainly food waste, the Mojokerto City Government has introduced a community BSFL growing program. A Similar study showed early good development results with this program, but we still do not know how environmentally sustainable, economically feasible, socially acceptable, institutionally backed, and technologically sound it is (Ferronato et al., 2024; Rehman et al., 2022; Tariq et al., 2025). Thus, a systematic sustainability assessment is required to quantify the strengths, constraints, and long-term prospects of this program.

To fill this gap, the current research utilizes the Multidimensional Scaling-Rapid Appraisal for Fisheries (MDS-RAPFISH) framework, which has been extensively used for quick assessments of sustainability in environmental management (Kavanagh and Pitcher, 2004; Pitcher and Preikshot, 2001). This study forms a nuanced profile of the sustainability of the BSFL cultivation program in Mojokerto City by examining five crucial dimensions of sustainability: environmental, economic, social, institutional, and technological. It also identifies specific qualities that could enable strategic improvements. This research is expected to contribute to better dialogue on sustainable urban waste management and provide a constructive reference for cities that want to adopt community-based bioresource strategies.

Most earlier studies on Black Soldier Fly Larvae (BSFL) have either been literature review-oriented or exploratory studies of organic waste management, highlighting biomass conversion efficiency, possible by-products, and waste reduction benefits. Widiyanto et al. (2024) stated that organic waste disposal to Black Soldier Fly Larvae (BSFL) can be an initiative to fulfil circular economy objectives. Similarly, Siddiqui et al. (2024) highlighted the ability to integrate BSFL into circular economy systems, thus decreasing waste management costs and generating economic benefits related to greater community welfare. However, studies investigating the sustainability of citywide BSFL activities, especially those that comprehensively integrate technical, social, economic, institutional, and environmental dimensions, are extremely rare (Hosseingholilou et al., 2025; Rehman et al., 2022; Tariq et al., 2025). Most pre-existing literature examines laboratory settings, small community groups, or pilot projects without assessing whether the program is effective and sustainable in the context of local policy implementation and urban waste management strategies.

Therefore, this research gap of the current study indicates that investigations to not only measure the technical capacities of Black Soldier Fly Larvae (BSFL) in the processing of organic waste but also to assess the effectiveness and sustainability of the implementation in actual urban scenarios are required. The contribution of this study is its integrated sustainability assessment approach to analyzing the BSFL cultivation program in Mojokerto city. The original contribution of this research is that it assesses how the program operates at the city level, including its enabling and constraining factors, and how the process generates economic value through the conversion of waste into valuable products. This study offers important empirical insights for policymakers, community waste management groups, and researchers who aspire to develop sustainable and effective organic waste management policies(KemenPANRB, 2011; PPN/Bappenas, 2020).

Based on these issues, this study aimed to assess the sustainability status of the BSFL cultivation program across environmental, social, economic, institutional, and technological dimensions. This study makes several contributions to the existing literature. First, it applies the Multidimensional Scaling–Rapid Appraisal for Fisheries (MDS–RAPFISH) framework to evaluate the sustainability of community-based black soldier fly larvae (BSFL) cultivation programs in the context of urban waste management, which has been under-explored in previous studies. Second, the analysis integrates environmental, social, economic, institutional, and technological dimensions simultaneously, providing a holistic assessment that goes beyond conventional technical or environmental evaluation. Third, this study empirically identifies key attributes that influence program sustainability at the city level, providing insights that can be applied to strengthen policy design and community-based organic waste management initiatives in the future. The results are expected to contribute to the formulation of strategies for enhancing the effectiveness and long-term sustainability of maggot-based programs in more integrated and sustainable organic waste management systems.

2. Methods

2.1 Type of Research

This study employed a quantitative approach with a descriptive–analytical research design. An evaluative component was also incorporated to assess the extent to which the maggot cultivation program achieved its intended objectives, particularly across the environmental, social, economic, institutional, and technological dimensions. Furthermore, this analysis aims to evaluate dimensions of sustainability using the Multidimensional Scaling (MDS) approach combined with a modified Rapid Appraisal for Fisheries (RAPFISH) method, which has been widely applied and further developed in sustainability assessments in the environmental, agricultural and natural resource management sectors (Abdillah et al., 2023; Lloyd Chrispin et al., 2022)

2.2 Research Location and Period

This study was conducted in Mojokerto City, East Java, Indonesia. The city was selected because it implemented a large-scale maggot cultivation program in 2023 as an innovative strategy for managing organic waste and supporting the adoption of a circular economy. The study will be conducted from August to November 2025.

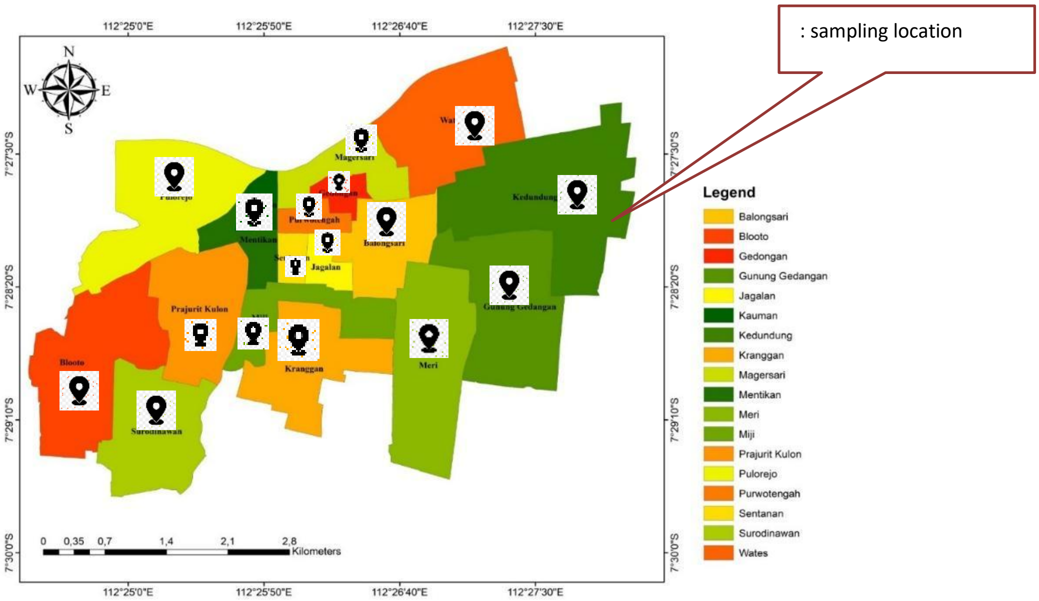

Figure 1. Research location (Mojokerto City)

Mojokerto City is located in East Java Province, Indonesia, between 7°27′0.16″ and 7°29′37.11″ South latitude and 112°24′14.3″ and 112°27′24″ East longitude (Figure 1). The city lies at the center of Mojokerto Regency, making it the core of socioeconomic and administrative activities in the surrounding region. In 2024, Mojokerto City had a total population of 142,272 (Statistics Bureau of Mojokerto City, 2024). The population distribution across urban villages (*kelurahan*) is highly uneven, with Wates Village having the highest population density (20,379 residents) and Purwotengah Village having the lowest population concentration (1,564 residents).

2.3 Data Collection

Using a descriptive quantitative research design, primary data were collected through closed-ended questionnaires, field observations, and direct measurements of the volume and weight of organic waste in the maggot cultivation units. Secondary data were obtained through document analysis, including Mojokerto City's waste generation data, the volume of waste processed, program reports, records of maggot and frass production, and other relevant documents. These data were statistically analyzed to describe the sustainability status and effectiveness of the program. These data were then statistically analysed to describe the sustainability status and effectiveness of the program.

The survey was conducted among program participants and community members involved in waste management using a closed-ended questionnaire with 69 respondents. The number of respondents was calculated using the Slovin method, with a margin of error of 5%. Sampling was conducted using purposive sampling with a population of 83. The sampling locations were spread across three sub-districts in Mojokerto City, where BSFL cultivation facilities were officially established by the city government. This spatial design helped ensure that the diversity of urban settings and operational scales present in the city were adequately represented. A map showing the sampling sites is included to illustrate the geographical extent of the study area. Assessments were performed to evaluate the state of maggot cultivation facilities, practices in use, and the sufficiency of ancillary equipment. Direct measurements were performed at the beginning and end of each bioconversion cycle to assess the effectiveness of organic waste reduction.

2.4 Data Analysis

To assess the sustainability of this program, this study employs Multidimensional Scaling (MDS) in conjunction with the Rapid Appraisal for Fisheries (RAPFISH) method. This approach has been widely adopted in diverse sectors, such as waste management and agriculture (Kavanagh & Pitcher, 2004). The selection of this approach is grounded in its availability to bring together several qualitative and quantitative markers into one integrated sustainability index, an approach that suits the complexity of multidimensional systems such as community-based waste management programs. This study examined sustainability indicators by converting them into quantitative indices in five broad dimensions: environmental, social, economic, institutional, and technological. Sustainability indices are then categorized into sustainability levels to provide a systematic assessment of the overall sustainability status of the program.

In multidimensional scaling (MDS) analysis, the objects under study are positioned within two or three dimensions to approximate their original relationships. The technique for determining ordination or distances in MDS is based on the squared Euclidean distance, which is calculated in n-dimensional space using the following formula:

$$\mathbf{d_{ij}}^2 = \sum(x_{ij} - x_j)^2 \tag{1}$$

where $d_{ij}{}^2$ are the computed Euclidean distances between the objects in the arbitrarily constructed plot, or called *euclidian squared distance*, where x_{ij} represents the attribute score value, and for all i, j = 1,2, ..., n. Because positive and negative discrepancies are equally undesirable, the sum of the squared errors for all proximities is taken, which yields the formula. (Manjunatha et al., 2024; Sukuryadi, 2025).

According to Faber in Fauzi (2019), sustainability as a concept requires further clarification into an operational definition that can be assessed through three key aspects: artifacts, goal orientation and interaction. The artifact aspect refers to the tangible characteristics of an object evaluated for its sustainability performance. The goal orientation aspect provides the basis or reference standard used to assess the sustainability of an object. The third aspect, interaction, is used to evaluate the changes experienced by an object as a result of internal and external interactions. The ability of an object to adapt gradually and continuously to internal and external changes serves as a determining factor in assessing its sustainability status(Faber et al., 2009).

In the context of organic waste management through maggot cultivation, sustainability indicators may include environmental aspects of waste management innovation, such as waste volume reduction, improved efficiency in converting waste into biomass, and potential impacts on soil and water quality. Economically, it contributes to cost-efficient production, creates market opportunities, and increases the value of maggot and compost products. Socially, it encourages community participation, enhances environmental awareness, and generates employment opportunities (FAO, 2014; Siddiqui et al. 2022). Furthermore, technological and institutional aspects have increasingly been incorporated as complementary dimensions in modern sustainability assessments(FAO, 2014; Santoso et al., 2023). To determine the sustainability of the maggot cultivation development program in Mojokerto City, several analytical stages were conducted: (1) identification of sustainability dimensions, namely environmental, economic, social, institutional, and technological; (2) selection of attributes for each dimension, established using an ordinal scale ranging from 0 to 3 (0 = very poor, 3 = very good); (3) scoring of each attribute based on the average values obtained from respondents' assessments; (4) operation of the MDS software; and (5) interpretation of the MDS outputs(Lloyd Chrispin et al., 2022; Santoso et al., 2023).

The determination of attributes and their numbers was based on previous studies, literature reviews, relevant regulations or policies, and expert judgment. Attribute data for each dimension were obtained through surveys using structured questionnaires administered to respondents who had participated in the training and mentoring activities under the program. The attribute scores were then analyzed using the Multidimensional Scaling (MDS) approach through the Rapid Appraisal for Fisheries (Rapfish) application to determine the sustainability status for each dimension. The MDS analysis generates a sustainability index ranging from 0 to 100, with the interpretation of the index values shown in Table 1.

Table 1. Sustainability status criteria (index score 0–100)

Score Range	Sustainability Status
0 – 25	Not Sustainable
26 – 50	Less Sustainable
51 – 75	Moderately Sustainable
76 – 100	Highly Sustainable

After the sustainability index values were obtained, a sensitivity (leverage) analysis was conducted to identify the most sensitive attributes and those with the greatest influence on sustainability status. Sensitive attributes are those with higher Root Mean Square (RMS) values on the X-axis, where larger RMS values indicate greater sensitivity and a stronger influence of the attribute on sustainability status(Josef Hae Jami et al., 2025; Santoso et al., 2023). In the final stage, a Monte Carlo analysis was performed to calculate the level of uncertainty resulting from random errors. The stages of the sustainability assessment using Multidimensional Scaling (MDS), Leverage Analysis, and Monte Carlo Analysis to determine the sustainability status of the maggot cultivation development program in reducing organic waste and enhancing the circular economy in Mojokerto City are as follows:

1. The attributes of the objects to be studied were determined for each dimension. The selection of attributes is based on previous research, literature studies, regulations/policies, and expert opinions, which will be adjusted to conditions in the field.
2. Conduct an assessment/scoring of the attributes that have been determined on an ordinal data scale in accordance with the results of the survey. Scoring was performed using a quantitative scoring scale for each sustainability indicator.
3. The scores for each attribute were then analyzed using a multidimensional scaling (MDS) approach with the rapid appraisal for fisheries (Rapfish) application to determine the sustainability status for each dimension expressed in terms of sustainability status. Once processed, the MDS produces a sustainability index (0–100). The interpretation is presented in Table 1.
4. Conduct a sensitivity analysis to determine which attributes are most sensitive and can affect sustainability status.
5. Perform Monte Carlo analysis to calculate aspects of uncertainty as a result of random errors.

2.5 Validity and Reliability

A validity test was conducted using content validity to ensure that the research instruments used for data collection were valid. This test was conducted by assessing the content of the questionnaire items through expert evaluation. Sampling was conducted using a purposive sampling method, which was considered appropriate given the study's objectives and characteristics. In this case, the evaluation was focused on the range, clarity, and relevance of the items of the questionnaire in relation to the subject of research, which was carried out by scholars, supervising instructors, and the Mojokerto City Environmental Agency. Content validity was used to investigate whether each item in the research tool corresponded with the concept being assessed. Construct validity determines the theoretical framework of an instrument, and criterion validity measures it against accepted external benchmarks. The computed r value is considered if it exceeds the tabulated r value.

A reliability assessment was conducted to gauge the internal consistency of the research instrument and identify the degree of consistency in measuring the same construct. The test employed Cronbach's alpha to assess the correlation among items within each variable. Because Cronbach's alpha prioritizes internal consistency (not temporal stability), this evaluation was based on data gathered from a single measurement occasion. The coefficient values can range from 0.0 to 1.0, and the larger the value, the better the reliability. A Cronbach's alpha value of 0.70 or greater is considered acceptable, and > 0.80 indicates good reliability. Therefore, in such a case, an instrument that meets the criteria below is considered reliable and acceptable for the statistical analyses that follow.

3. Result and Discussion

3.1. Overview of The Results of The Program Sustainability Analysis (MDS/RAPFISH)

The program's performance in terms of sustainability was assessed across multiple environmental, economic, social, institutional, and technological dimensions based on a set of established criteria. These factors are the main factors used in the MDS/RAPFISH analysis, and they guide the assessment of the overall sustainability level of the program. A summary of the scoring attributes employed in the analysis is presented in Table 2 in the Supplementary Files.

The sustainability potential of the maggot cultivation program in Mojokerto City is based on its sustainability index value. The sustainability assessment of the maggot cultivation program in Mojokerto City used the MDS-RAPFISH approach by analyzing 35 attributes or parameters, as shown in Table 2 above, resulting in a total sustainability index of 54,22 on a scale of 0–100, with a stress value of 0,13 and a Squared Correlation (RSQ) of 0,95. Based on the interpretation criteria used in this study, a score of 0–25 indicates not sustainable, 26–50 indicates less sustainable, 51–75 indicates moderately sustainable, and 76–100 indicates highly sustainable. The results of the multidimensional analysis showed a moderately sustainable status(Abdillah et al., 2023; Santoso et al., 2023).

Dimensional analysis revealed a heterogeneous pattern: the environmental dimension ranked the highest (74.97), followed by the social (66.34), institutional (65.82), technological (61.70), and economic dimensions (60.92). These results suggest that the program is achieving considerable ecological benefits, particularly by reducing organic waste, cutting greenhouse gas emissions, and providing beneficial by-products. Nevertheless, progress is subject to many social, economic, institutional, and technical challenges that may impede the attainment of full sustainability. As noted by Singh et al. (2021), analyses performed on an experimental scale showed that organic waste reduction efficiency varies from 60% to 72%. Under well-controlled conditions, Black Soldier Fly (BSF) larvae can reduce organic waste mass by 60–72%. The bioconversion efficiency of BSF larvae, which can degrade 50–70% of the originally produced organic waste mass in a short time, is remarkable (Barragán-Fonseca et al., 2017). In addition to minimizing the quantity of organic waste, the development of black soldier larvae provides livestock with high-protein feed, organic fertilizers, and economically valuable products, thus promoting a circular economy (Surendra et al., 2016).

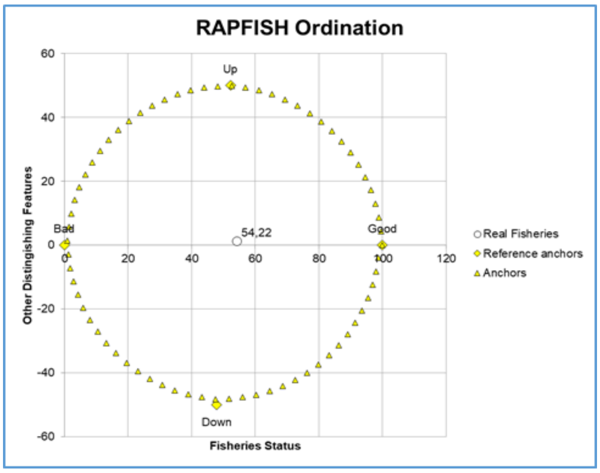

Figure 3. Multidimensional sustainability index of maggot cultivation programs in Mojokerto City

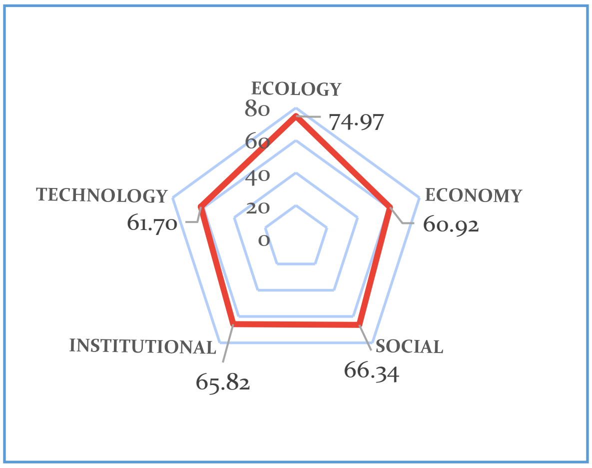

Figure 4. Contribution of each dimension to the maggot cultivation program in Mojokerto City

3.2. Sensitive Factors Influencing the Sustainability Index of the Maggot Cultivation Program

3.2.1. Environmental Dimension

The elevated score in the environmental dimension (74.97) indicates that BSF larvae have an efficient capability to reduce organic waste and are effective in reducing greenhouse gas emissions. Notable factors include reduced organic waste disposal, decreased odor and pest presence, and the production of beneficial residues (frass) that improve soil quality. These observations are consistent with the technical expectations for the use of Black Soldier Fly as a nature-based solution, which could offer swift ecological advantages. However, given that this score is somewhat below the > 75 level required to determine that this program is fully sustainable, a continued emphasis on the quality of raw materials (mainly in relation to inorganic contamination), ensuring a steady supply of organic waste, and stronger biosecurity measures, so that environmental performance continues to sustain and improve, are imperative.

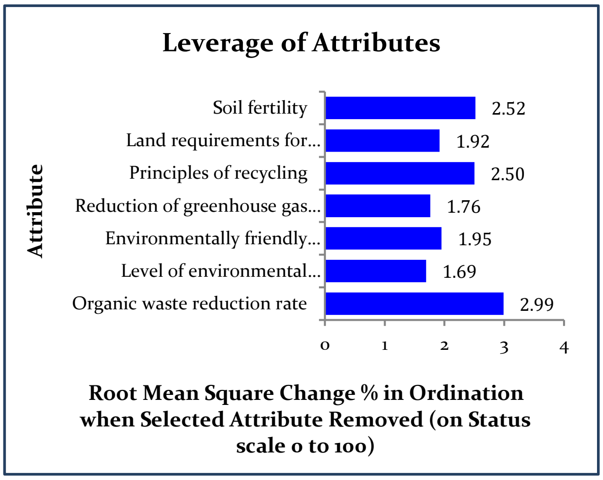

Figure 5. Sensitivity analysis of environmental dimensions

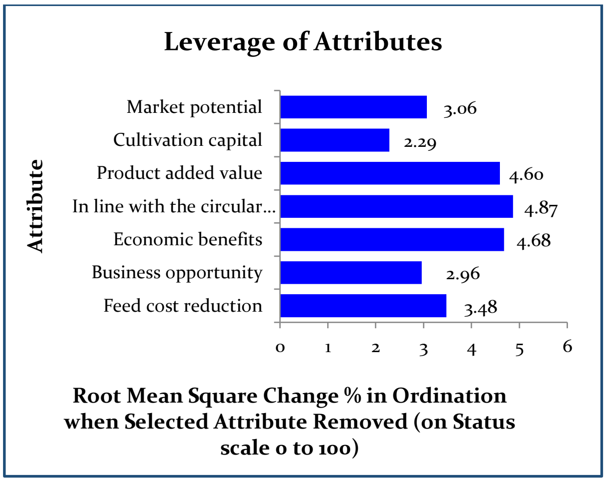

Figure 6. Sensitivity analysis of economic dimensions

Sensitivity analysis (leverage) indicates that the rate of organic waste reduction is the most sensitive factor influencing the sustainability of the maggot cultivation program in Mojokerto, as reflected by the leverage value of 2.99, as shown in Figure 5. This finding indicates that the maggot cultivation program is recognized for its significant contribution to reducing organic waste (Camperio et al., 2025). These results are consistent with previous research, which highlighted that BSF have a very high bioconversion capacity, capable of decomposing 50-70% of the initial organic waste mass in a relatively short time (Barragán-Fonseca et al., 2017). The latest research also states that the main findings show that BSFL-based bioconversion can reduce the volume of organic waste by up to 85.5%, significantly reducing dependence on landfills and greenhouse gas emissions(Anokye, 2025).

Singh et al. (2021) demonstrated a reduction efficiency of 60–72% on an experimental scale. Life Cycle Assessment-based research also confirms that BSF technology can significantly reduce GHG emissions compared to conventional composting methods (Ferronato et al., 2024; Smetana et al., 2019). These results indicate that the environmental dimension is an important benefit of maggot cultivation programs in Mojokerto City and support BSF as an ecological approach to enhance the circular economy and sustainable waste management. The development of maggot farming programs in Mojokerto City reflects the strong compatibility between Black Soldier Fly (BSF) bioconversion and the city's dominant organic waste profile. The high performance of environmental indicators demonstrates the effectiveness of BSF larvae in rapidly reducing organic waste volume, mitigating environmental nuisances such as odor and leachate, and lowering potential greenhouse gas emissions associated with landfill-based waste disposal. By using the biological transformation of organic waste to obtain larval biomass and nutrient-rich by-products, the BSF system can serve as an environmentally sustainable way to handle source-separated waste, reducing its negative ecological impact. These findings situate BSF as a nature-based solution for sustainable urban waste management, supporting circular economy principles by using waste to create usable resources.

3.2.2. Economic Dimension

Economically, the prospects are promising, although the situation is not yet fully stable. The revenue received from the sale of maggots and frass, together with the small capital requirements and feed costs, are important advantages for these purposes. However, several key issues continue, such as supply uncertainties (in terms of volume and capacity as well as a nascent market), price fluctuations, relatively small production scales, and high-scale potential, which do not allow for a large number of larger firms to be interested in this activity. Notably, this sector will benefit more from focused interventions along the value chain. These measures would involve enforcing uniform product quality, developing cooperatives and joint marketing initiatives, and launching short-term incentive schemes to support RW's upscaling of production activities in a more standardized fashion.

The sensitivity analysis (leverage) shows that the alignment of features with the circular economy has the strongest influence on the sustainability of maggot cultivation activity in Mojokerto City, with a leverage of 4.87 (Figure 6). The characteristics of economic benefits (4.68) and economic value and their derivatives (4.60) are equally important. Together, these three attributes contribute significantly to the program's sustainability. In practice, if they do not improve these features, the city government could find that the economic value of the sustainability matrix is drastically affected. According to a properly functioning circular economy framework, the material flow (organic waste → maggots → feed/frass → market) of this program heavily impacts its financial viability (Surendra et al., 2016; Van Huis and Oonincx, 2017). When this process fails to run effectively, such as when no one is willing to buy maggots and frass, or these materials are underutilized, the economics will be reduced in such a way that the program becomes largely about making the environment greener. Furthermore, the notions of economic benefits as well as the value of products or by-products indicate both material benefits (such as increased income and cost reductions) and the total market demand for maggot products, which play a significant role in the sustainability of the program. However, this study also identified a gap in the form of suboptimal marketing channels and the absence of local regulations supporting the formal commercialization of maggot products. These findings emphasize that long-term economic sustainability requires stronger institutional support and cross-sector collaboration among the government, MSMEs, community groups, and the private sector(Anokye, 2025).

Conversely, feed cost reduction (3.48), market potential (3.06), business opportunities (2.96), and cultivation capital (2.29) had moderate impacts. This indicates that the other characteristics should still be strengthened, although their influence is not as strong as that of the high-value attributes. This is consistent with previous studies on BSFL cultivation results, which showed that although BSFL could save feed costs and help generate revenue, the economic benefits are often limited at the small or community scale owing to erratic supply, non-unified markets, and low production numbers (Makkar et al., 2014; Smetana et al., 2019; Surendra et al., 2016). Other studies have pointed out that the potential value of BSFL products for the market and business opportunities of BSFL products are strongly related to the existence of structured value chains, stable demand, and quality assurance mechanisms, which are not well preserved in community-based initiatives (Gold et al., 2018). According to the human-centered perspective, this situation proves that locals are gaining some economic and environmental positive benefits from RW, but overall sustainability can be maintained only with institutional support, wider markets, and continuous technical support (Diener et al., 2011a; Ferronato et al., 2024). Hence, the leverage analysis informs clear priorities, and the most effective means to support the integration of circular economy mechanisms and the maggot product value chain is to promote economic resilience and the well-being of those communities in question (Surendra et al., 2016).

3.2.3. Social Dimension

The social dimension score indicates improved public acceptance, driven by direct impacts, including a cleaner environment and small-scale job opportunities. However, participation rates are still lopsided, with some RW units being very active while others are passive, and negative feelings towards maggots are still common among certain residents. A further reason for the lower score is the lack of public knowledge and involvement in waste management and the lack of integration of the program into community education. This is because the public lacks awareness of and participation in waste management, while also being poorly integrated into structured community education activities. Educational interventions through behavior change communication and the promotion of the empowerment of susceptible groups should result in increased adoption and social adaptation of the programs.

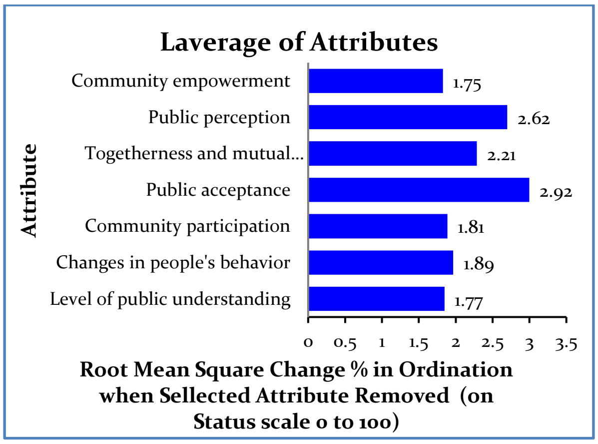

Figure 7. Sensitivity analysis of social dimensions

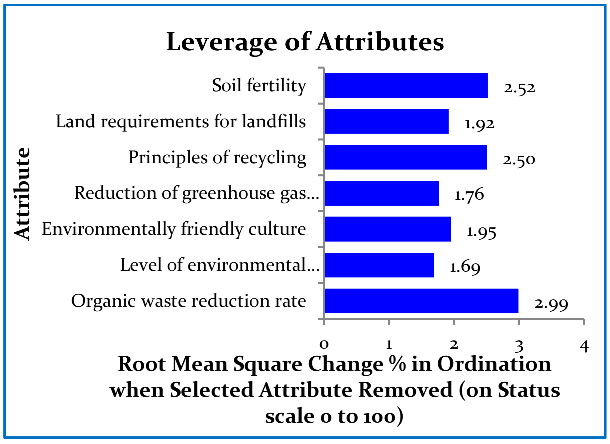

Figure 8. Sensitivity analysis of institutional dimensions

According to the social dimension leverage analysis, community acceptance (2.92) and community perception (2.62) are the most critical factors influencing the sustainability of the maggot cultivation program as a strategy to reduce organic waste in Mojokerto City. These results are in strong accord with field environments, which place heavy demands on the social acceptability of innovations for maggot-based waste management for further dissemination. However, it must be stressed that the acceptance of insect-based innovations in the public domain is significantly dictated by understanding, risk perception, and trust in the technology's benefits. Therefore, significant influence scores in community acceptance and perception were observed in this study, suggesting that the success of the program is not just the result of technological factors, but also residents feeling comfortable, confident, and able to acknowledge the value of maggot cultivation practices (Anokye, 2025; Tariq et al., 2025).

Other attributes also play a key role in shaping a supportive social ecosystem, such as social cohesion and mutual cooperation (2.21), as well as behavior change (1.89). This aligns with Sulistyaningsih (2022), who found that waste management success at the community level is greatly influenced by a culture of mutual cooperation, active community participation, and behavioral changes toward more responsible waste management practices. The lower leverage scores observed in the areas of empowerment, understanding, and participation indicate that while these factors remain relevant, they are not the primary drivers of changes in sustainability status. These three factors provide a set to trigger when knowledge improves, empowerment increases, and participation increases; the groundwork for greater public acceptance and positive public perception is established. Overall, these results confirm that the social dimension is a fundamental pillar that cannot be ignored, and the success of maggot cultivation as part of the circular economy is highly dependent on the community's perception, acceptance, and involvement in the process.

3.2.4. Institutional Dimension

In the institutional dimension, the program received a sustainability score of 65.82, indicating that institutional capacity remains weak in terms of regulatory frameworks, budgetary support, infrastructure provision, and the absence of clearly defined and active management teams within the program, despite initial government support. The lack of program integration into regional development planning, absence of periodic evaluation mechanisms, and unclear incentive structure hinder the development of a solid institutional foundation (Anokye, 2025; Sapanli et al., 2023). To strengthen this dimension, firm institutional commitment is required, including the formulation of local regulations that formally recognize RW-level maggot units as instruments for organic waste management at the urban-village level, the allocation of routine budgets (from the local budget or grants), and the establishment of collaborative mechanisms across government agencies (Environmental Agency, Agriculture Agency, Cooperatives Agency) and the private sector to support long-term program sustainability.

Sensitivity analysis (leverage) indicated that the provision of training (4.00) had the greatest influence on changes in the sustainability status of the maggot cultivation program. This conclusion is particularly significant for Mojokerto City, as the effectiveness of organic waste management through maggot cultivation depends on business operators' understanding of cultivation methods, feed management, and the effective use of end products. In other words, there is a strong impact on program effectiveness for enhancing human resource capacity, as maggot cultivation technology requires skill sets that are not available to all involved parties. Additionally, partnerships with the private sector (3.90) and cross-sector collaboration (3.74) played a huge role in contributing to the sustainability of the program, suggesting that the effectiveness of local government, communities, and business cooperation in promoting product use, technical support, and market building is critical. Without this connectivity, the value chain cannot develop smoothly within the circular economy framework.

There are medium-leverage features such as regulatory support, management institutions, budget, and infrastructure, without which there would be no basis to sustain a program, as regulatory stability and financial and institutional support are of great importance to ensure sustainable and continuous activity. However, leverage analysis suggests that the most significant changes occur when capacity building and partnership networks are strengthened. This implies that the sustainability of the maggot cultivation program is influenced not only by formal institutions but also by human capacity and the strength of multi-stakeholder collaboration. Therefore, the best way to reduce organic waste and promote a circular economy in Mojokerto City is to emphasize training, network development, and cross-sectoral collaboration.

This is supported by research conducted by Diener et al. (2011), who emphasized that the success of Black Soldier fly cultivation depends heavily on the technical capacity of the practitioners, ranging from feed management and larval rearing to waste processing. In addition, Gold et al. (2018) indicated that the black soldier fly value chain can thrive when strong partnerships with the private sector are established, particularly for product absorption, technological support, and market access.

3.2.5. Technological Dimension

The technological dimension shows that the Black Soldier Fly (BSF) cultivation program is in agreement with the local background considering the tropical climate and low-cost operational model, but also that there are some shortcomings in the operational capacity. Cultivation methods are still manual and primitive, and the availability of higher-end tools is poor. Low-cost technical solutions, such as basic monitoring kits, weather-resistant enclosure structures, and visual procedural guides, combined with technology transfer through a local technical support center, would increase technical sustainability and allow for more widespread replication of the program (Anokye, 2025; Rehman et al., 2022).

The leverage analysis of the technological dimension revealed that processing technology (3.95) and technological efficiency (3.92) exerted the greatest influence on the sustainability of the maggot cultivation program in Mojokerto City. These findings are consistent with those of Gold et al. (2018), who confirmed that the successful use of Black Soldier Fly (BSF) in reducing organic waste is highly dependent on appropriate processing technology that is easy to operate and capable of increasing the conversion of waste into biomass. Good technological efficiency not only accelerates the decomposition process but also increases larval productivity, ultimately strengthening the potential for a circular economy. This is in line with the research by Smetana et al. (2019), who showed that BSF performance increases significantly when the technology system is standardized. High technological efficiency not only accelerates the decomposition process but also increases larval productivity, ultimately strengthening the potential for circular economy development (Avilés-Palacios and Rodríguez-Olalla, 2021; Bahtiar and Kamelia, 2023; Smetana et al., 2019).

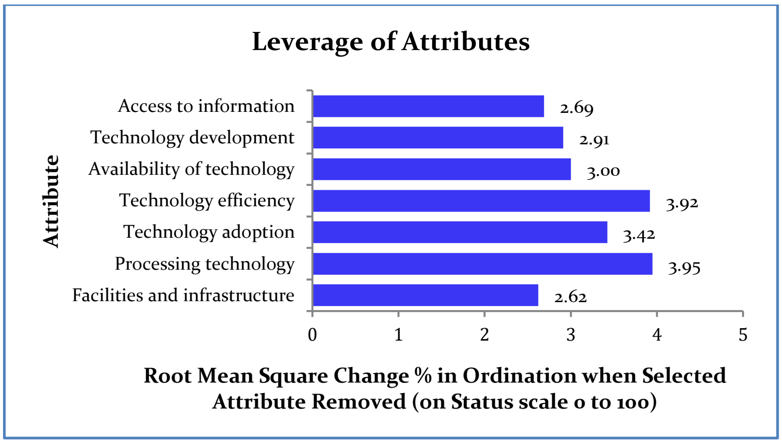

Figure 9. Sensitivity analysis of technological dimension

The high-leverage attributes of technology adoption (3.42) and technology provision (3.00) further indicate that sustainability is not only dependent on the availability of tools but also on the readiness of communities and operators to implement them to their full potential. The adoption of waste processing technologies is heavily dependent on access to information, training support, and infrastructure readiness(Anokye, 2025). These findings are consistent with previous research showing that the successful implementation of BSF in various countries is highly dependent on minimal infrastructure readiness, technical support, and easily replicable operational procedures(Mertenat et al., 2019). Leverage scores were lower for facilities and infrastructure (2.62) and access to information (2.69) than for other dimensions. This suggests that while these are matters, they are not decisive for sustainability. However, they are critical enablers for ensuring the optimal utilization of existing technologies. The financial viability and marketability of BSFL products are affected by low levels of technological readiness, economies of scale, and technology facilities (Gold et al., 2018).

Overall, these findings confirm that strengthening processing technologies, improving efficiency, and accelerating technology adoption are key strategies for enhancing the sustainability of maggot cultivation as a practical solution for reducing organic waste in Mojokerto City(Anokye, 2025; Widiyanto et al., 2024).

4. Conclusions

The results of this study show that the maggot cultivation program in Mojokerto City has implemented meaningful and measurable ecological advantages, as evidenced by an environmental sustainability index score of 74.95. It has proven effective in minimizing the amount of organic waste, improving the quality of the residential environment, and supporting the principles of the circular economy through the utilization of larvae and frass as valuable products. The positive outcomes show that the community directly gained a cleaner and healthier environment while also substantiating that black soldier fly (BSF) bioconversion provides an environmentally friendly solution for urban waste management.

The overall sustainability index score of 54.22 means that the program is classified in the "moderate sustainability" category and should be developed on several dimensions, including social, economic, institutional, and technological. The non-uniform extent of community involvement, underdeveloped market chain for BSF-larva-based products, non-standardized scope of technical SOPs, and lack of government policy support all demonstrate that ecological success has not been fully reciprocated by the readiness of supporting systems. With reinforced community, private sector, and local government collaboration, improved technical capacity, and the incorporation of the program in city-level policies, the BSF larva cultivation program could represent one more potential step in a positive, inclusive, and welfare-enhancing sustainability management context. More research is needed on the sustainability of maggot waste management in terms of spatial and temporal scope. Longitudinal investigations are required to evaluate the sustainability and long-term feasibility of the maggot cultivation program and to evaluate long-term behavior consistency, market dynamics, and institutional endorsement of growth-inclination. Furthermore, it may be useful to incorporate life cycle assessment (LCA) and economic feasibility in prospective research to evaluate environmental benefits and value chain performance more broadly. More important would be comparative studies in different cultures, policy frameworks, and socioeconomic environments to evaluate the scalability and transferability of maggot-mediated bioconversion as a model for sustainable urban waste management.

In general, the current study provides empirical evidence that the maggot cultivation program in Mojokerto City is progressing towards more sustainable waste management, but it must be improved in terms of governance, integration in the value chain, and uniformity in practice at the community level. These findings suggest potential economic sustainability in practice through policy intervention, incentivizing waste segregation, developing maggot product standards, technology training of practitioners, and access to markets. This study not only fills a void in research on BSF-based programs in smaller Indonesian cities but also provides a foundation for relevant and flexible waste management and circular economy policies.

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Ethics Statement

This study was conducted in accordance with the principles of research ethics. Respondent participation was voluntary, and verbal consent was obtained prior to data collection. The respondents were informed of the research purposes, and their confidentiality and anonymity were fully guaranteed. No personal or sensitive data were collected, and this study did not involve vulnerable groups or clinical interventions.

Credit Author Statement

Lilis Sugiyarni: Conceptualization, Methodology, Investigation, Collection of Data, Data Curation, Data Analysis, Visualization, Writing Original Draft, Review, and Editing. **Nuhfil Hanani**: Supervision, Methodology, Validation, Review, and Editing. **Bunga Hidayati**: Supervision, Methodology, Data Validation, Review, and Editing. **Dini Atikawati**: Data Curation, Investigation, Review, and Editing. **Nazilatul Azizah Mohd Radzi**: Formal Analysis, Validation, Review, and Editing.

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