

# DECENTRALIZED APPROACHES TO BLACK SOLDIER FLY WASTE MANAGEMENT FOR ENHANCING COMMUNITY RESILIENCE

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**Abstract.** This study explores the potential of decentralized waste management systems utilizing Black Soldier Fly (BSF, *Hermetia illucens*) larvae as a sustainable approach to enhance community resilience and circular economy practices. The research aims to assess how BSF-based bioconversion can effectively reduce organic waste while generating valuable by-products such as animal feed and organic fertilizer. Using a mixed-method approach, both field experiments and qualitative analyses were conducted to evaluate waste reduction efficiency, biomass yield, and socio-environmental impacts within community-scale waste management systems. The findings indicate that decentralized BSF waste management significantly contributes to reducing the volume of organic waste by up to 70–80%, while producing high-protein larvae biomass (approximately 40–45% protein content) suitable for animal feed production. Additionally, the residual frass serves as a nutrient-rich compost, improving soil fertility and supporting local agricultural productivity. From a socio-economic perspective, the implementation of BSF systems fosters community participation, generates income opportunities, and reduces dependency on centralized waste collection services. The study also highlights key success factors, including public awareness, local policy support, and technical capacity building for maintaining consistent system performance. Overall, this research demonstrates that decentralized BSF waste management represents a viable, eco-innovative, and community-empowering strategy for sustainable waste handling in urban and rural settings. By integrating biological waste conversion with local governance and community engagement, the BSF model strengthens resilience, resource efficiency, and environmental sustainability at the grassroots level..

**Keywords:** Black Soldier Fly; decentralized waste management; circular economy; community resilience; sustainable bioconversion

## I. INTRODUCTION

Rapid urbanization and population growth have intensified the global waste management crisis, particularly in developing countries where municipal waste systems remain inadequate and centralized collection infrastructures are often overburdened [1]. Organic waste constitutes approximately 50–60% of total municipal solid waste, most of which ends up in landfills or open dumpsites, contributing to greenhouse gas (GHG) emissions and environmental pollution [2]. As a result, sustainable and decentralized waste management strategies have become a pressing need to address environmental degradation, improve public health, and promote local economic development [3]. Among emerging biological waste management innovations, the Black Soldier Fly (BSF, *Hermetia illucens*) has gained increasing attention due to its remarkable ability to bioconvert various organic wastes including food residues, livestock manure, and agricultural by-products into valuable resources such as protein-rich larvae and organic fertilizer [4], [5]. The larvae feed on organic substrates, reducing waste volume efficiently while producing biomass that can serve as animal feed or bioenergy feedstock [6]. The residue (frass) left after larvae

feeding is a nutrient-dense compost suitable for soil enrichment, making BSF systems a core component of the circular bioeconomy [7].

Traditional, centralized waste treatment approaches are capital-intensive, energy-demanding, and often inaccessible to low-income communities [8]. In contrast, decentralized BSF-based waste management systems are low-cost, scalable, and socially inclusive, allowing households and communities to independently process waste at the local level [9]. This decentralization reduces waste transportation costs, minimizes methane emissions, and fosters local participation in sustainable resource management [10]. Studies have demonstrated that small-scale BSF operations can achieve 70–80% organic waste reduction and generate substantial environmental and socio-economic benefits, particularly in urban and peri-urban areas [11]. In addition to their environmental value, BSF systems play a crucial role in enhancing community resilience the capacity of communities to adapt to and recover from environmental and economic disturbances [12]. By integrating BSF cultivation with community-based waste governance, local stakeholders can strengthen food security, income diversification, and environmental awareness [13]. Moreover, BSF larvae production offers an alternative protein source for livestock feed,

reducing dependence on fishmeal and mitigating pressure on marine ecosystems [14]. The residual compost further contributes to soil restoration, supporting sustainable agriculture in rural and urban farming contexts [15]. Despite growing global recognition of BSF's potential, implementation at the community scale faces multiple challenges, including inconsistent technical knowledge, insufficient policy support, and social acceptance issues [16]. Decentralized models require not only biological optimization but also effective coordination among local authorities, private sectors, and citizen groups [17]. Therefore, there is a need for an integrated framework that connects biological waste valorization, socio-economic empowerment, and policy innovation to ensure the sustainability of BSF waste management systems [18].

This study aims to analyze the role of decentralized BSF waste management in enhancing community resilience, focusing on both its environmental performance and socio-economic impacts. The research evaluates waste reduction efficiency, biomass productivity, and social participation levels in community-scale BSF projects. The findings are expected to contribute to sustainable waste management discourse by providing a model for environmentally sound, economically viable, and socially inclusive waste management systems in line with the Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production) [19]. Decentralized waste management (DWM) is an emerging paradigm that emphasizes localized waste treatment and resource recovery rather than relying solely on centralized municipal systems [20]. Unlike conventional models that depend on large-scale transport and landfill operations, DWM promotes distributed infrastructure, allowing communities, small enterprises, or cooperatives to manage waste independently at the source [21]. This approach not only reduces transportation costs and greenhouse gas (GHG) emissions but also increases participation, accountability, and environmental awareness among citizens [22].

In developing countries, DWM plays a crucial role in bridging infrastructure gaps and addressing inefficiencies in waste collection and disposal. Studies in Southeast Asia and Sub-Saharan Africa have shown that decentralized systems, when properly managed, can process up to 60–80% of organic waste locally, thereby alleviating pressure on municipal waste systems [23]. Moreover, DWM aligns with circular economy principles, focusing on waste valorization—transforming waste into valuable resources through composting, anaerobic digestion, or insect bioconversion [24]. However, the success of DWM depends on community engagement, financial viability, and supportive policy frameworks that ensure proper waste segregation, technology adoption, and market linkages for end products [25].

Among the biological waste valorization technologies, Black Soldier Fly (BSF, *Hermetia illucens*) larvae bioconversion has gained global attention as a sustainable, efficient, and low-cost method for organic waste management

[4], [5]. The larvae feed voraciously on decomposing organic matter, converting it into two high-value products: larvae biomass (rich in protein and lipids) and frass residue (a nutrient-rich organic fertilizer) [26]. This process achieves a dual benefit waste reduction and resource recovery supporting the concept of a closed-loop bioeconomy [7]. BSF-based systems are particularly advantageous for decentralized settings because they require minimal energy input, limited land area, and simple infrastructure. Research indicates that BSF larvae can reduce organic waste by up to 70–80% within 10–14 days, depending on substrate composition and environmental conditions [11], [27]. The harvested larvae contain approximately 40–45% crude protein and 30–35% fat, making them an excellent alternative protein source for aquaculture and poultry industries [14]. In addition, the frass enhances soil fertility by increasing organic carbon, nitrogen, and microbial activity [15]. Recent studies also highlight BSF's environmental benefits in reducing methane emissions, a key contributor to global warming. According to Gold et al. [5], substituting conventional composting or landfilling with BSF bioconversion could mitigate 47–60% of methane emissions from organic waste streams. This positions BSF technology as a cornerstone of climate-smart waste management, particularly in rapidly urbanizing regions [28].

Community resilience refers to the capacity of social systems to adapt, absorb, and recover from disturbances whether environmental, economic, or social while maintaining essential functions [12]. In the context of waste management, resilience is strengthened when communities possess localized capabilities to manage waste sustainably and derive socio-economic benefits from the process [13]. BSF-based decentralized systems exemplify this by transforming waste challenges into livelihood opportunities through local entrepreneurship, job creation, and food security enhancement [10]. Empirical evidence from Indonesia, Kenya, and the Philippines shows that community-scale BSF projects can create circular value chains linking waste producers, farmers, and feed manufacturers, fostering inclusive local economies [9], [13]. By empowering residents to take ownership of waste management, BSF projects also enhance social cohesion and environmental stewardship key components of long-term community resilience [29]. Furthermore, integrating BSF farming into local educational and cooperative programs increases environmental literacy and strengthens adaptive capacities in the face of climate and waste management challenges [16].

Effective governance and policy integration are critical to scaling up decentralized BSF waste management initiatives. Governments and local authorities play a vital role in providing technical support, regulatory frameworks, and financial incentives for community-based operations [17]. According to Müller and Patel [17], policy alignment across sectors waste management, agriculture, and energy is essential to avoid regulatory overlap and ensure that BSF-derived products meet safety and environmental standards. Public-private partnerships (PPP) have also emerged as successful governance models for implementing BSF projects at scale. PPPs facilitate knowledge transfer, improve operational standards, and enhance the commercialization of BSF products [18]. Furthermore, policy

incentives such as subsidies for organic waste segregation and tax benefits for circular economy initiatives can encourage community adoption and private sector participation [25]. Without institutional support and inclusive governance, BSF projects risk remaining small-scale pilot programs with limited long-term impact [23].

While BSF technology has been widely studied in controlled laboratory environments, its decentralized and community-based implementation remains underexplored. Most existing research focuses on technical efficiency and waste reduction metrics, with limited attention to social, economic, and governance dimensions that determine long-term sustainability [16], [29]. Therefore, this study addresses this gap by examining how decentralized BSF waste management contributes to both environmental outcomes and community resilience. The conceptual framework (Figure 1) proposes that decentralized BSF systems enhance community resilience through three key mechanisms:

- (1) Resource efficiency: reducing waste volume and producing valuable outputs (protein and fertilizer).
- (2) Economic empowerment: creating livelihood opportunities and local business models.
- (3) Social inclusion: strengthening community participation and awareness in sustainable waste governance.

This integrative perspective aligns with the triple-bottom-line framework of sustainability (environmental, economic, and social), offering a comprehensive lens for analyzing the multidimensional impact of BSF-based decentralized waste management systems [24].

## II. RESEARCH METHODS

This study employed a mixed-method research design that integrated quantitative field experimentation with qualitative community assessment to comprehensively evaluate the environmental and socio-economic impacts of decentralized Black Soldier Fly (BSF) waste management systems. The research was conducted in Denpasar, Bali, Indonesia, where community-based BSF units have been established as part of local waste reduction initiatives. Quantitative data were collected through controlled bioconversion trials conducted at three decentralized BSF facilities, focusing on waste reduction rate (%), larval biomass yield (g/kg waste), and frass quality (N–P–K nutrient composition). Each site processed household organic waste for 14 days using standardized BSF rearing protocols. Environmental parameters including temperature, humidity, and substrate composition were monitored daily to evaluate their influence on larval performance [30].

To capture the social and institutional dimensions, qualitative data were gathered through semi-structured interviews and participatory observations involving 30 stakeholders, including community leaders, local waste managers, and residents directly engaged in BSF activities. The interviews explored perceptions of BSF technology,

community participation, policy support, and economic benefits. Data triangulation was applied to ensure reliability between field observations, quantitative outcomes, and stakeholder narratives. Quantitative data were analyzed descriptively using SPSS 26.0 to determine mean values, correlations, and percentage reductions, while qualitative data were thematically coded following Braun and Clarke's (2006) framework [31]. Ethical clearance and informed consent were obtained prior to data collection, ensuring compliance with research ethics for environmental and social studies [32].

## III. RESULTS AND DISCUSSION

### *Waste Reduction Efficiency and Larval Performance*

The results of the bioconversion trials demonstrated that the decentralized Black Soldier Fly (BSF) waste management units achieved a high waste reduction rate, ranging between 70% and 82% within a 14-day processing cycle. The average waste reduction efficiency across the three community units was 76.8%, consistent with findings from Surendra et al. [26] and Arancon et al. [30], who reported similar reduction rates under tropical conditions. The larval biomass yield averaged  $145 \pm 12$  g per kg of organic waste, with a protein content of approximately 42.6% and lipid content of 32.1% on a dry-weight basis. These values confirm the suitability of BSF larvae as a sustainable source of animal feed protein [14], [33]. Environmental monitoring indicated that optimal larval growth occurred at a temperature range of 27–32°C and humidity levels between 60–75%, consistent with the thermophilic and moisture-dependent nature of BSF larvae [5]. The substrate composition—dominated by vegetable residues (48%) and food scraps (35%)—provided sufficient nutrients for larval development. Statistical analysis showed a strong correlation between substrate nitrogen content and larval growth rate ( $r = 0.82$ ,  $p < 0.05$ ), supporting the hypothesis that nutrient-rich substrates enhance conversion efficiency [34]. These results reinforce BSF's role as an efficient bioconverter capable of transforming organic waste into high-value biomass, offering a sustainable alternative to landfilling and composting.

Table 1. Infrastructure development for decentralized BSF treatment

| Component              | Details                                                                              | Key Features/Specifications                                                          |
|------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Modular units          | Design flexibility and scalability to suit different environments and waste volumes. | Tailored to local needs, easily replicated.                                          |
| Controlled environment | Maintaining optimal growth conditions for BSF larvae.                                | Temperature: $26 \pm 3^\circ\text{C}$ , Humidity approximately 40%, Proper aeration. |
| Real-time monitoring   | Use of IoT technology to continuously monitor and adjust environmental conditions.   | Sensors for temperature, humidity, and pH levels.                                    |
| Automated feeding      | Automated systems to deliver consistent and optimal amounts of waste to the larvae.  | Mechanized feed systems that adjust to waste type and volume.                        |
| Harvesting technology  | Technologies for efficient harvesting of mature larvae and processing of frass.      | Automated collection and separation systems.                                         |

### *Quality of Frass and Soil Fertility Potential*

The frass (residual substrate) generated from BSF processing exhibited promising characteristics as an organic fertilizer. Laboratory analysis revealed mean nutrient concentrations of N = 3.1%, P = 1.8%, and K = 1.5%, alongside high organic carbon content (29.4%) and low moisture level (11%). These parameters meet the quality standards for organic fertilizers recommended by the Food and Agriculture Organization (FAO) [35]. Similar to findings by Roffeis et al. [15], frass derived from BSF bioconversion significantly improves soil structure, microbial activity, and nutrient retention capacity. Field trials with frass application on local vegetable plots indicated a 22% increase in crop yield compared to untreated control plots, confirming its agronomic value. Farmers participating in the pilot trials reported reduced dependency on synthetic fertilizers and a visible improvement in soil texture after three months of use. The dual benefit of waste reduction and soil enrichment underscores BSF's alignment with circular economy principles, converting waste into renewable agricultural inputs [7], [24].

### *Socio-Economic Impacts and Community Participation*

Beyond environmental outcomes, the implementation of decentralized BSF waste management systems generated significant socio-economic benefits. Interviews revealed that approximately 65% of participants perceived BSF activities as economically beneficial, particularly through the sale of larvae for feed and the commercialization of frass as organic fertilizer. Average income from larvae sales reached IDR 25,000–35,000 per kg, with additional revenue from frass amounting to IDR 5,000 per kg. These figures correspond to the findings of Suryawan and Adnyani [29], who emphasized that BSF initiatives enhance local livelihoods by integrating waste management with micro-entrepreneurship. Community participation proved essential for sustaining BSF systems. Local residents contributed to daily waste collection, larvae feeding, and product marketing, reflecting a collaborative governance model that fosters ownership and trust. The active involvement of community members aligns with Gupta and Sharma's [22] conclusion that participation strengthens decentralized waste management efficiency and social accountability. Moreover, participants reported improved environmental awareness and reduced household waste disposal costs, reinforcing the resilience-building aspect of the BSF approach [12], [13].

### *Environmental and Resilience Outcomes*

The integration of BSF technology within community waste systems contributed directly to climate mitigation and adaptive capacity. Lifecycle analysis estimated a 47% reduction in methane emissions compared to traditional composting and an 80% decrease in waste transported to centralized facilities, significantly lowering the carbon footprint of local waste management [28]. These results are comparable to those of Gold et al. [5], who found that BSF systems substantially reduce GHG emissions and waste transport dependency. From a resilience perspective, decentralized BSF initiatives enhanced the adaptive capacity

of communities by diversifying livelihoods, promoting food system circularity, and strengthening environmental stewardship. This aligns with the framework of Aldunce et al. [12], which defines resilience as the ability to adapt, learn, and reorganize in response to environmental disturbances. The BSF model, by transforming waste into resources and engaging citizens in circular practices, provides a tangible pathway toward community-based resilience and sustainable urban governance [9], [36].

The empirical results validate the theoretical proposition that decentralized waste management, when integrated with biological valorization technologies such as BSF, enhances both environmental sustainability and community resilience. The findings corroborate earlier studies highlighting the efficiency and socio-economic inclusivity of BSF based circular systems [7], [9], [27]. The integration of environmental, economic, and social benefits supports the triple-bottom-line approach, reinforcing BSF's role as a scalable model for sustainable development [24]. Theoretically, this study extends the literature on community-based circular economy models by illustrating how local bio-waste management can drive systemic transformation in resource governance. Practically, it demonstrates that decentralized bioconversion technologies require supportive policy frameworks, technical training, and public awareness programs to maintain continuity and efficiency [17], [18], [25]. The BSF model, therefore, offers a replicable and adaptable strategy for cities seeking to reduce waste volumes, create local value chains, and promote environmental justice in the context of sustainability transitions [20], [37], [38].

From a policy standpoint, this study highlights the need for integrated, multi-level governance to mainstream BSF-based waste management into urban and rural development planning [39]. Policymakers should provide institutional support through standardized regulations for BSF-derived products, capacity-building programs for local operators, and financial incentives for small-scale circular economy enterprises [40], [41]. Furthermore, collaborative partnerships among local governments, academic institutions, and private stakeholders are essential to enhance technology diffusion, quality control, and market access for larvae and frass products [42]. Long-term sustainability also requires public education campaigns and community training to maintain operational consistency and social acceptance. Ultimately, decentralized BSF systems represent a transformative pathway toward sustainable, inclusive, and climate-resilient waste governance, aligning with the United Nations Sustainable Development Goals (SDGs)—particularly SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production) [43].

## **IV. CONCLUSION**

This study demonstrates that decentralized waste management systems utilizing Black Soldier Fly (BSF) larvae represent an effective and sustainable approach for addressing organic waste challenges while simultaneously enhancing community resilience. The results confirm that community-based BSF systems achieved an average waste reduction rate of

76–80%, transforming household organic residues into high-protein larvae and nutrient-rich organic fertilizer. These outcomes not only contribute to environmental sustainability through reduced methane emissions and landfill dependency but also generate economic value by creating income opportunities for local households. Moreover, the participatory nature of decentralized BSF initiatives strengthens social cohesion, environmental awareness, and adaptive capacity at the community level. By closing material loops and promoting localized resource recovery, the BSF model exemplifies the principles of a circular bioeconomy and offers a replicable framework for sustainable waste management across developing regions.

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