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Application of Analytical Hierarchy Process (AHP) to Assess Bio and Thermal-Conversion Technology Options for Organic Solid Waste Management

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ABSTRACT

Indonesia is increasingly challenged by the management of organic solid waste, especially in Bali Province, where organic waste accounts for about 68% of the total municipal waste produced. The current waste management strategies mainly depend on landfilling and basic composting techniques, which are inadequate to mitigate the environmental and socio-economic effects. This research utilizes the Analytical Hierarchy Process (AHP) to systematically assess and prioritize eight bioconversion and thermal-conversion technologies for managing organic waste in Bali. The evaluation considers four main criteria, environmental, social, technical, and economic, along with their sub-criteria, based on expert opinions and literature review. The results reveal that bioconversion technologies, particularly composting, black soldier fly (BSF) processing, and eco-enzyme production, are the most appropriate choices, as they offer high community acceptance, reduced greenhouse gas emissions, and better compatibility with local waste characteristics and socio-economic conditions. Thermal technologies like incineration and gasification are less favored due to their higher environmental risks and capital expenses. The findings offer a comprehensive decision-support framework for policymakers and practitioners to create sustainable organic waste management strategies tailored to Indonesia's context.

INTRODUCTION

Managing organic waste effectively is an escalating environmental issue globally, especially in developing areas where organic materials make up most of the municipal solid waste. Despite this, such waste is frequently disposed of through unsustainable practices like landfilling, which exacerbates environmental harm and increases greenhouse gas (GHG) emissions (Yensukho et al. 2022, Gunamantha et al. 2023a). In Bali Province, Indonesia, organic waste accounts for about 68% of the municipal waste stream and is predominantly sent to landfills (Gunamantha et al. 2023c), highlighting the pressing need for sustainable processing technologies.

Recent studies indicate that selecting appropriate organic waste treatment technologies necessitates a balanced assessment of environmental, economic, technical, and social factors (Abu et al. 2021, Gunamantha et al. 2023b). Multi-Criteria Decision-Making (MCDM) tools, such as the Analytic Hierarchy Process (AHP), have been extensively used for this purpose. AHP is particularly effective in decision-making environments with varied and conflicting goals, as it enables structured comparisons among different options (Kurbatova & Abu-Qdais 2020, Siejka 2020, Sun et al. 2020).

Numerous studies have employed AHP to aid in solid waste management planning, including technology selection (Afrane et al. 2022, Agbejule et al. 2021), landfill siting (Mallick 2021), and system optimization (Apaydin & Akçay Han 2023, Fogarassy et al. 2022). For example, Afrane et al. (2022) utilized AHP-

TOPSIS to assess waste-to-energy options in Ghana, while Apaydin & Akçay Han (2023) applied AHP to evaluate collection methods within a zero-waste policy framework.

However, much of the existing research is narrowly focused on established solutions like composting or anaerobic digestion, often neglecting emerging alternatives such as black soldier fly (BSF) larvae bioconversion, eco-enzyme production, or newer thermal treatments like gasification and pyrolysis (Siciliano et al. 2021, Benny et al. 2023, Torres-Lozada et al. 2023). These technologies are gaining attention for their potential in circular economies and their adaptability to decentralized systems in resource-constrained settings (Abu-Qdais et al. 2025).

To address this gap, the current study uses AHP to evaluate a wider range of organic waste processing technologies tailored to Bali's socio-environmental context. These include composting, BSF, anaerobic digestion, eco-enzyme production, pyrolysis, gasification, incineration, and RDF (refuse-derived fuel) production. This approach allows for a systematic comparison based on environmental, social, technical, and economic criteria (Paul & Paul 2021, Abu et al. 2021).

The novelty of this research lies in its integrated evaluation of underutilized yet promising bioconversion and thermal conversion technologies through an AHP-based framework. By contextualizing these options within Bali's waste management priorities, this study offers actionable insights for stakeholders aiming to divert organic waste from landfills while promoting community involvement and income generation (Abu-Qdais et al. 2025, Gunamantha et al. 2023, 2023b, 2023c).

MATERIALS AND METHODS

Research Framework and Approach

The Analytical Hierarchy Process (AHP) was employed in this study as the primary method for evaluating and ranking organic waste treatment technologies in Bali Province, Indonesia. This multi-criteria decision-making (MCDM) approach was selected due to its effectiveness in handling complex decision problems that integrate both qualitative and quantitative factors, particularly in contexts where stakeholder preferences must be aligned with sustainability objectives.

The research framework consists of four main stages:

1. Identification of criteria and sub-criteria based on a comprehensive literature review and expert consultations.
2. Selection of alternative technologies, comprising both bioconversion and thermal-conversion options, chosen for their relevance to Indonesia's waste management challenges.
3. Pairwise comparisons and judgment elicitation from a panel of experts to evaluate the relative importance of criteria and alternatives.
4. Synthesis of priorities and consistency analysis to ensure the reliability of the results.

Selection of Criteria and Sub-Criteria

Four main criteria were used to evaluate the technologies: Environmental, Social, Technical, and Economic. These criteria reflect the priorities of sustainable waste management in tropical and developing regions and were aligned with previous AHP applications in the waste sector (Kurbatova & Abu-Qdais 2020, Siejka 2020, Sun et al. 2020).

Each main criterion was further broken down into sub-criteria to reflect specific dimensions relevant to the Bali context:

- Environmental: Greenhouse gas emissions, occupational and community health risks, and water/soil pollution.
- Social: Community acceptance, job creation, and responsible management.
- Technical: Feasibility and sustainability, energy recovery, material recovery, technological complexity.
- Economics: Capital investment, operational/maintenance costs, revenue potential.

Table 1 delineates each sub-criterion, illustrating how various aspects of sustainability—consistent with global indicators and adapted to local environmental and socio-economic contexts-are integrated into the analysis, as supported by previous studies (Kurbatova & Abu-Qdais 2020, Siejka 2020, Sun et al. 2020).

Selection of Alternative Technologies

Eight organic waste processing technologies were selected for evaluation:

- Bioconversion Technologies: Composting, Black Soldier Fly (BSF) processing, Anaerobic Digestion (AD), and Eco-Enzyme production.
- Thermal Conversion Technologies: Incineration, Gasification, Carbonization (slow pyrolysis), and Drying & Compaction (RDF production).

Table 2 enumerates the eight determined technological alternatives, along with concise descriptions of their primary products and roles in waste valorization. These technologies were chosen based on their relevance to Indonesia's organic waste profile, technical maturity, and evidence from global case studies (Babalola 2015, Kurbatova & Abu-Qdais 2020, Sun et al. 2020, Gunamantha et al. 2023b).

Expert Panel Composition

The AHP analysis relied on expert judgments from six qualified professionals:

- Three academic experts from Universitas Pendidikan Ganesha.
- Three practitioners from government agencies overseeing waste management in Bali.

All experts had a minimum of 10 years of experience in solid waste management and demonstrated familiarity with AHP methodology, ensuring reliable and context-aware input.

Pairwise Comparisons and Data Collection

Experts participated in structured interviews and completed Saaty's pairwise comparison questionnaires to evaluate:

Table 1: main criteria, sub-criteria, and brief description.

No.	Criteria	Sub-criteria	Description
1.	Environmental	Global warming	Referring to the selected technology's ability to reduce greenhouse gas emissions and other pollutants.
		Occupational and public health	Referring to the selected technology's ability to reduce risks to the health of workers and the surrounding community.
		Water and soil pollution	Refers to the selected technology with the least environmental impact on water and soil
2.	Social	Community acceptability:	Referring to the selected technology that is accepted as appropriate, valid, or suitable by the community.
		Job creation	Referring to the selected technology's ability to generate the most employment opportunities.
		Responsible management group	Referring to the selected technology with a clear and accountable management structure.
3.	Technical	Feasibility and sustainability	Referring to the selected technology that can be practically implemented and sustainably operated.
		Energy recovery	Refers to the selected technology with the highest potential for energy production.
		Technological sophistication	Referring to the selected technology that is advanced and requires skilled human resources.
		Material recovery	Referring to the selected technology with the highest potential for material recovery.
4.	Economic	Investment cost	Referring to the selected technology with the lowest initial investment cost.
		Operation and maintenance cost	Referring to the selected technology with the lowest operational and maintenance expenses.
		Revenue	Referring to the selected technology with the highest potential revenue generation.

Table 2: Technology options.

No.	Conversion Method	Kinds of Technology	Description
1.	Thermal conversion	Drying and compaction	The main product of the compaction and drying process is RDF solid fuel, which is converted into electrical energy.
		Incineration	The main product of the incineration process is hot gas, which is converted into electrical energy.
		Gasification	The main product of the gasification process is gas fuel (syngas), which is converted into electrical energy.
		Carbonization (slow pyrolysis)	The main product of the slow pyrolysis process is biochar, which is used as a soil conditioner.
2.	Bioconversion	Anaerobic Digestion	The main products of the AD process are biogas, which is converted into electrical energy and digestate, which is stabilized into compost.
		Composting	The main product of the composting process is biogas.
		Black Soldier Fly (BSF) Process	The main products of the BSF process are larvae, which are used as animal feed and residues, which are stabilized into compost.
		Eco-enzyme Manufacturing Process	The main product of the eco-enzyme manufacturing process is a liquid that can be used as a disinfectant and a residue that is stabilized into compost.

- The relative importance of criteria and sub-criteria.
- The comparative performance of each alternative technology against each sub-criterion.

The geometric mean method was used to consolidate individual judgments into group consensus matrices (Saaty 1987).

Consistency and Validity Testing

Consistency Ratios (CRs) were calculated for all pairwise matrices. A CR of less than 0.1 was considered acceptable, following AHP standards. Validity checks covered:

- Comparisons among the main criteria
- Sub-criteria matrices
- Technology alternative evaluations

This step ensured that expert judgments were logically consistent and robust (Siejka 2020).

Priority Synthesis and Final Ranking

The Average Normalized Column (ANC) method was used to synthesize priorities through:

- Matrix normalization
- Local and global weight calculation
- Aggregation of weights to derive final technology rankings

This method maintains methodological transparency and supports reproducibility in technology evaluation.

Sensitivity Analysis

In this study, a sensitivity analysis was conducted to evaluate the robustness of the AHP results by assessing how variations in criteria weights affected the final ranking of waste treatment alternatives. This technique was considered essential in Multi-Criteria Decision Analysis (MCDA) for examining the stability of outcomes under different decision-making scenarios (Babalola 2015, Kurbatova & Abu-Qdais 2020, Sun et al. 2020). Multiple scenarios were explored by systematically altering the weights assigned to the four main criteria. In the first scenario, full weight (1.0) was assigned to one criterion while the others were given a weight of zero, resulting in four possible configurations. In the second scenario, equal weights (0.5) were allocated to two criteria, with the remaining two set to zero, generating six combinations. The third scenario involved assigning a weight of 0.33 to three criteria, while the fourth was assigned zero, producing four additional combinations. Finally, an equal weight of 0.25 was applied to all four criteria in a balanced scenario. This approach provides valuable insights into how shifting stakeholder priorities influence the selection of optimal organic waste processing technologies.

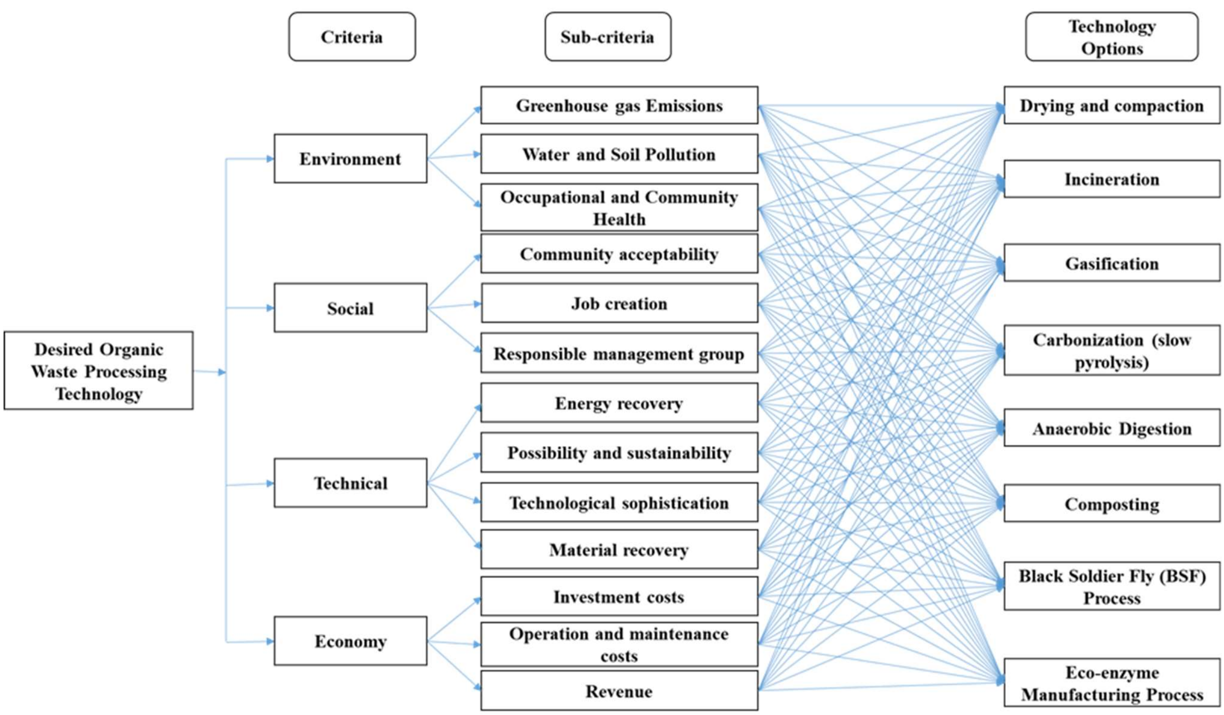

Fig. 1: Levels of criteria used in technological selection.

Table 3: Pairwise comparison matrix and weights for main criteria relative to objectives.

Criteria	Environment	Social	Economy	Technic	Weight	Consistency ratio
Environment	1.000	1.732	4.189	4.857	0.492	0.068147
Social	0.577	1.000	3.533	0.907	0.253	
Economy	0.239	0.283	1.000	1.089	0.107	
Technical	0.206	1.103	0.918	1.000	0.148	

RESULTS AND DISCUSSION

The process starts with establishing a structured hierarchy (Fig. 1) that begins with the goal and progresses through intermediate levels (criteria) down to the lowest level, which consists of a set of alternatives. This hierarchical framework is based on best practices from numerous previous AHP applications in solid waste and energy system planning (Siejka 2020, Sun et al. 2020, Agbejule et al. 2021, Afrane et al. 2022). The objective is to identify the most suitable technology for processing organic waste. To achieve this, a series of questions has been formulated at the first level: "How strong and significant is one criterion compared to other criteria in determining the choice of organic waste processing technology?" At the second level, the question is: "How strong and significant is one sub-criterion compared to other sub-criteria in relation to the main criterion?" Finally, at the third level, a matrix has been prepared to assess: "How strongly and significantly does one alternative compare to other alternatives in contributing to the sub-criteria?"

According to the combined assessments of experts, Environmental criteria were identified as the most crucial element in choosing a technology for organic waste treatment, carrying a weight of 0.492. This highlights the increasing concern about environmental effects, especially greenhouse gas (GHG) emissions, which play a major role in climate change in Indonesia (Gunamantha et al. 2023a). This concern is further emphasized by the impacts on climate, emissions from landfills, and health risks in areas with high population density or tourism (Yensukho et al. 2022, Gunamantha et al. 2023b). Subsequently, the Social (0.253), Technical (0.148), and Economic (0.107) criteria were prioritized, mirroring consistent trends observed in similar global settings (Kurbatova & Abu-Qdais 2020, Abu et al. 2021). Table 3 presents the results of the pairwise comparison matrix for the main criteria in relation to the primary objectives.

Table 4 presents the weights assigned to the sub-criteria under the environmental criterion, revealing that greenhouse gas emissions and occupational and community health are the top priorities, each with a weight of 0.353. These are followed by water and soil pollution, which hold a slightly lower weight of 0.294. This distribution indicates that the primary focus in selecting organic waste processing technologies is on minimizing emissions and protecting public and worker health. These findings align with those of Agbejule et al. (2021), who similarly ranked health impacts and greenhouse gas emissions as the most critical environmental concerns, with pollution potential receiving relatively less emphasis. This prioritization is also supported by broader literature highlighting the waste sector's significant contribution to air pollution and its implications for public health (Gunamantha et al. 2023b, Degefu & Asefa 2024, Saghi et al. 2024).

Table 5 shows that within the social criteria, community acceptability holds the highest weight (0.366), followed by job creation (0.337), and responsible management group (0.297). The prioritization of community acceptance reflects the importance of participatory approaches in improving the adoption of waste management technologies, as supported by Agbejule et al. (2021) and Saifi & Jha (2024). In the technical criteria (Table 6), feasibility and sustainability dominate with a weight of 0.455, indicating a strong preference for technologies that are easy to implement and maintain in localized settings. This is followed by energy recovery (0.270), material recovery (0.192), and technological sophistication (0.084), consistent with the emphasis on operational simplicity highlighted by Paul & Paul (2021). Table 7 presents the economic sub-criteria, where revenue generation ranks highest (0.403), followed by operational and maintenance costs (0.345), and investment costs (0.252). This contrasts with previous studies such as Agbejule et al. (2021), who identified investment costs as the most critical, and Qazi et al. (2018), who emphasized operational expenses.

Table 4: Pairwise comparison matrix and weights for environmental sub-criteria.

Sub-criteria	Greenhouse Gas Emissions	Water and Soil Pollution	Occupational and Community Health	Weight	Consistency ratio
Greenhouse Gas Emissions (GHG)	1.000	1.201	1.000	0.353	0
Water and Soil Pollution (WSP)	0.833	1.000	0.833	0.294	
Occupational and Community Health (OPH)	1.000	1.201	1.000	0.353	

Table 5: Pairwise comparison matrix and weights for social sub-criteria.

Sub-criteria	Community acceptability	Job creation	Responsible management group	Weight	Consistency ratio
Community acceptability (CA)	1.000	1.081	1.238	0.366	0
Job creation (JC)	0.925	1.000	1.132	0.337	
Responsible management group (RMG)	0.808	0.884	1.000	0.297	

Table 6: Pairwise comparison matrix and weights for technical sub-criteria.

Sub-criteria	Energy recovery	Feasibility and sustainability	Technological sophistication	Material recovery	Weight	Consistency ratio
Energy recovery (ER)	1.000	0.785	2.877	1.201	0.270	0.02637
Feasibility and sustainability (PS)	1.274	1.000	4.886	3.625	0.455	
Technological sophistication (TS)	0.348	0.205	1.000	0.354	0.084	
Material recovery (MR)	0.833	0.276	2.821	1.000	0.192	

Table 7: Pairwise comparison matrix and weights for economic sub-criteria.

Sub-criteria	Investment costs	Operation and maintenance costs	Revenue	Weight	Consistency ratio
Investment costs (IC)	1.000	0.450	0.964	0.252	0.09799
Operation and maintenance costs (OMC)	2.221	1.000	0.533	0.345	
Revenue (RV)	1.037	1.877	1.000	0.403	

The high priority given to revenue reflects growing interest in circular economy models and entrepreneurship in waste management, as echoed by Afrane et al. (2022) and Torres-Lozada et al. (2023).

Based on Tables 3 to 7, the final weights of all sub-criteria are consolidated and presented in Table 8. The results show that the three environmental sub-criteria rank first, second, and third overall. This outcome is expected, given that the environmental criterion received the highest overall weight compared to the other main criteria.

As shown in Table 9, bioconversion methods outperform thermal technologies under the environmental criterion. Black Soldier Fly (BSF) processing (0.215) and composting (0.213) receive the highest environmental weights, indicating their strong performance in reducing greenhouse gas emissions (GHG), minimizing occupational and public health (OPH) risks, and limiting water and soil pollution (WSP). These results align with evidence from field implementations in both urban and rural settings, which highlight the environmental benefits of BSF and composting methods (Dzepe et al. 2021, Fogarassy et al.

Table 8: Final calculation of sub-criteria.

Criteria	Weight of Criteria	Sub-criteria	Weight of sub-criteria	Weight Total of sub-criteria
Environment	0.492	Greenhouse Gas Emissions	0.353	0.174
		Water and Soil Pollution	0.294	0.145
		Occupational and Community Health	0.353	0.174
Social	0.253	Community acceptability	0.366	0.093
		Job creation	0.337	0.085
		Responsible management group	0.297	0.075
Technical	0.107	Energy recovery	0.270	0.029
		Feasibility and sustainability	0.455	0.049
		Technological sophistication	0.084	0.009
		Material recovery	0.192	0.021
Economy	0.148	Investment costs	0.252	0.037
		Operation and maintenance costs	0.345	0.051
		Revenue	0.403	0.060

2022, Madonsela et al. 2024). In contrast, incineration scores the lowest (0.037), reinforcing longstanding concerns about its contribution to air pollutants and toxic residue generation (Tait et al. 2020). Their systematic review found consistent associations between proximity to waste incinerators and elevated risks of respiratory problems, cancer, and adverse birth outcomes, emphasizing their potential public health hazards. These comparative scores support the prioritization of bioconversion technologies in environmentally sensitive waste management strategies.

Table 10 presents the relative weights of each technology option based on the social criteria. Among the alternatives, Composting ranks highest in overall social performance with a global weight of 0.226, driven by strong community acceptance (0.238) and high job creation potential (0.230). Eco-enzyme manufacturing follows with a global weight of 0.172, supported by balanced performance across all three sub-criteria, particularly in its ability to be managed by local groups (0.163). Black Soldier Fly (BSF) processing and drying, and compaction are tied at a global weight of 0.139, showing moderate community acceptability and organizational feasibility. In contrast, incineration and gasification are the lowest ranked (both at 0.068), indicating limited social acceptability and low employment creation, which aligns with previous findings that suggest low public support for high-tech and centralized waste solutions in community settings. These results underscore a strong preference for socially inclusive and participatory waste treatment methods that align with local capacities and community engagement.

As shown in Table 11, among all alternatives, incineration achieves the highest overall technical score (0.163), primarily due to its top ranking in feasibility and sustainability (0.243) and strong performance in technological sophistication (0.217), reflecting its advanced capabilities in high-energy recovery systems. Composting follows with a global weight of 0.139, supported by its high score in material recovery (0.210) and feasibility (0.164), making it well-suited for decentralized applications. Eco-enzyme production ranks third (0.132), showing balanced performance across feasibility (0.152) and material recovery (0.187). Technologies like carbonization and gasification also perform well in energy recovery but fall short in feasibility and sustainability, affecting their total technical weight. Meanwhile, BSF processing and anaerobic digestion show moderate scores, particularly in material recovery and feasibility, reinforcing their relevance in local, low-tech contexts. Drying and compaction, although technically consistent, rank lower overall due to relatively modest scores across all sub-criteria. In line with the previous studies (Sun

Table 9: Weight of each technology option relative to environmental sub-criteria.

Technology Options/Alternative	Environment (0.492)			Global Weight of Environment
	GHG (0.353)	OPH (0.294)	WSP (0.353)	
Drying and compaction	0.069	0.066	0.103	0.080
Incineration	0.032	0.031	0.046	0.037
Gasification	0.068	0.056	0.088	0.072
Carbonization (slow pyrolysis)	0.059	0.082	0.100	0.080
Anaerobic Digestion	0.108	0.112	0.130	0.117
Composting	0.258	0.173	0.201	0.213
Black Soldier Fly (BSF) Process	0.212	0.253	0.186	0.215
Eco-enzyme Manufacturing Process	0.194	0.227	0.146	0.187

Table 10: Weight of each technological option relative to sociocultural.

Technology Options/Alternative	Social (0.253)			Global Weight of Social
	CA (0.366)	JC (0.337)	RMG (0.297)	
Drying and compaction	0.112	0.196	0.109	0.139
Incineration	0.087	0.047	0.068	0.068
Gasification	0.062	0.057	0.087	0.068
Carbonization (slow pyrolysis)	0.073	0.107	0.128	0.101
Anaerobic Digestion	0.073	0.096	0.098	0.088
Composting	0.238	0.230	0.208	0.226
Black Soldier Fly (BSF) Process	0.143	0.134	0.140	0.139
Eco-enzyme Manufacturing Process	0.213	0.134	0.163	0.172

Table. 11: Weight of each technology option relative to technical sub-criteria.

Technology Options/Alternative	Technical (0.107)				Global Weight of Technical
	ER(0.270)	PS (0.455)	TS (0.084)	MR (0.192)	
Drying and compaction	0.123	0.118	0.076	0.117	0.116
Incineration	0.098	0.243	0.217	0.039	0.163
Gasification	0.214	0.059	0.178	0.066	0.112
Carbonization (slow pyrolysis)	0.223	0.055	0.215	0.096	0.122
Anaerobic Digestion	0.129	0.089	0.118	0.122	0.109
Composting	0.070	0.164	0.058	0.210	0.139
Black Soldier Fly (BSF) Process	0.065	0.120	0.069	0.162	0.109
Eco-enzyme Manufacturing Process	0.077	0.152	0.070	0.187	0.132

Table 12: Weight of each technology option relative to economic sub-criteria.

Technology Options/Alternative	Economy (0.148)			Global Weight of Economy
	IC (0.252)	OMC (0.345)	RV (0.403)	
Drying and compaction	0.056	0.063	0.105	0.078
Incineration	0.228	0.138	0.058	0.128
Gasification	0.171	0.134	0.100	0.130
Carbonization (slow pyrolysis)	0.212	0.115	0.148	0.153
Anaerobic Digestion	0.171	0.170	0.116	0.148
Composting	0.056	0.115	0.145	0.112
Black Soldier Fly (BSF) Process	0.059	0.127	0.180	0.131
Eco-enzyme Manufacturing Process	0.047	0.137	0.148	0.119

et al. 2020), these results highlight that while incineration excels in advanced technical metrics, simpler technologies like composting and BSF offer a better fit for practical, scalable, and sustainable applications, especially in resource-constrained or decentralized environments.

Table 12 outlines the economic outcomes of different technological options. Carbonization, or slow pyrolysis, stands out as the most economically beneficial, boasting the highest global economic weight (0.153) due to its significant revenue potential (0.148) and relatively favorable investment cost (0.212). Anaerobic digestion is a close second (0.148), showing a well-rounded performance across all sub-criteria. The Black Soldier Fly (BSF) process also demonstrates strong economic performance (0.131), driven by the highest revenue score (0.180), highlighting its considerable income-generating potential. Gasification (0.130) and incineration (0.128) produce moderate results but are limited by lower revenue contributions. Composting (0.112) and eco-enzyme manufacturing (0.119) show strengths in revenue generation with lower investment needs but are hindered by higher operational costs. Drying and compaction rank the lowest (0.078), indicating minimal economic attractiveness. Overall, the table emphasizes that revenue potential is the key economic factor, favoring technologies that enable marketable outputs and entrepreneurial opportunities.

Discussion

Analysis given in Table 13 reveals a distinct preference for bioconversion technologies, such as Composting, Black Soldier Fly (BSF) Processing, and Eco-Enzyme Production, due to their strong performance in environmental, social, and feasibility aspects. These technologies are well-aligned with Bali's sustainability goals, particularly in minimizing greenhouse gas emissions, enhancing health, and encouraging community involvement. Their decentralized and cost-effective nature makes them particularly suitable for both rural and urban areas in developing regions. This trend is consistent with global findings that highlight the importance of local engagement for effective and sustainable waste management solutions (Yan et al. 2020, Sunarti et al. 2024). On the other hand, thermal technologies like incineration and gasification, despite their technical capabilities and potential for energy recovery, are less preferred due to environmental concerns and limited public acceptance. Even mid-range options such as carbonization and anaerobic digestion show potential but lack the comprehensive benefits of the top three methods. Overall, the findings suggest a significant policy implication: future

Table. 13: Ranking results based on global weight.

Technology Options/Alternative	Global Weight of Environment (0.497)	Global Weight of Social (0.253)	Global Weight of Technical (0.107)	Global Weight of Economy (0.148)	Global Weight
Drying and compaction	0.080	0.139	0.116	0.078	0.099
Incineration	0.037	0.068	0.163	0.128	0.072
Gasification	0.072	0.068	0.112	0.130	0.084
Carbonization (slow pyrolysis)	0.080	0.101	0.122	0.153	0.101
Anaerobic Digestion	0.117	0.088	0.109	0.148	0.113
Composting	0.213	0.226	0.139	0.112	0.193
Black Soldier Fly (BSF) Process	0.215	0.139	0.109	0.131	0.172
Eco-enzyme Manufacturing Process	0.187	0.172	0.132	0.119	0.167

waste management strategies should focus on bioconversion pathways that combine environmental performance with social inclusivity and operational feasibility.

Based on the sensitivity analysis, Fig. 2 shows that under the first scenario-where one criterion is assigned full weight (1.0), and the remaining three are set to zero-pyrolysis experiences a notable increase in ranking, while the other technologies display both positive and negative shifts. When the environmental, social, or technical criteria individually receive full weight, composting consistently ranks highest. Conversely, when the economic criterion alone is emphasized, pyrolysis takes the top position. In the second scenario (Fig. 3), where pairs of criteria are equally weighted at 0.5, and the others are excluded, ranking fluctuations are observed across all technologies. Composting maintains the lead when combinations such as environmental-sociocultural, environmental-technical, sociocultural-technical, and sociocultural-economic are used. However, BSF becomes the top-ranked option under the environmental-economic pairing, while incineration takes the lead when technical and economic criteria are prioritized together.

In the third scenario (Fig. 4), when the environmental criterion is weighed at zero and the other three at 0.333 each, composting still emerges as the best choice across all combinations. In the fourth scenario (Fig. 5), where all main criteria are equally weighed at 0.25, composting continues to be the preferred option.

The sensitivity of the outcomes across the four scenarios reveals a consistent trend, where bioconversion-based processing technologies (such as composting, BSF, and eco-enzyme) are generally the most favourable options for handling organic waste. In contrast, gasification and other thermal conversion-based technologies are considered the least favourable choices. Although combinations of criteria weights can lead to countless scenarios, certain features distinctly demonstrate how results vary with changes in weights (Babalola 2015).

To select the appropriate technology, it is crucial to evaluate various criteria using a multi-criteria approach. The findings in this study illustrate how pairwise comparisons help establish priorities among criteria and processing technology options. The synthesis of priority criteria in

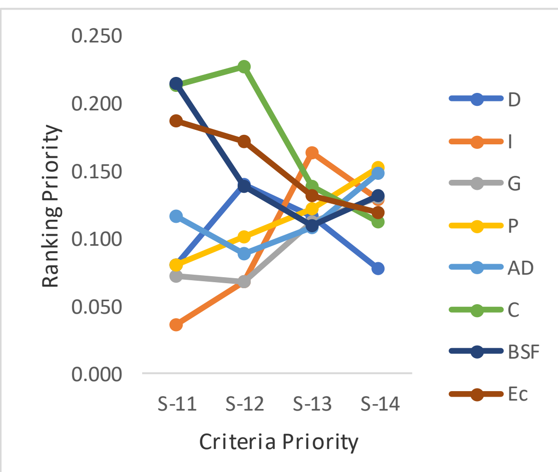

Fig. 2: Scenario I.

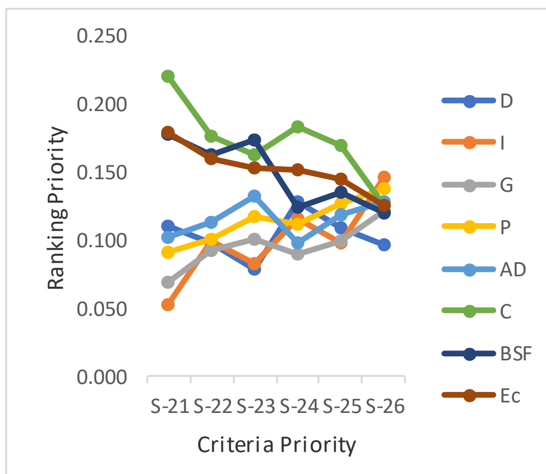

Fig. 3: Scenario II.

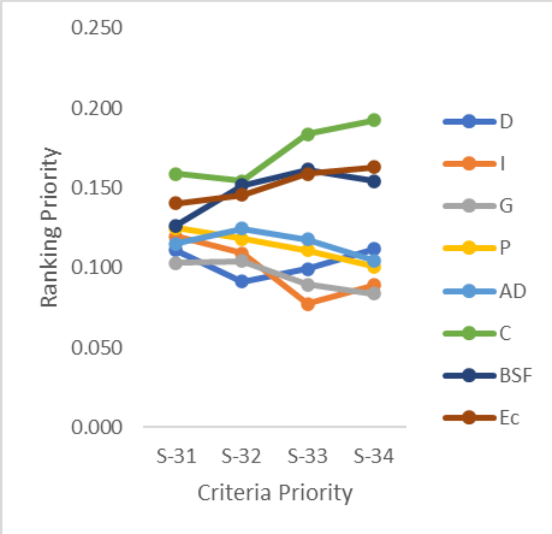

Fig. 4: Scenario III.

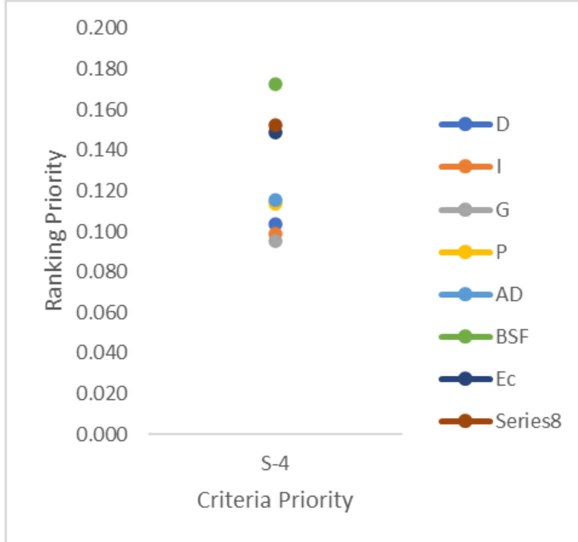

Fig. 5: Scenario IV.

relation to objectives and options, as shown in Table 13, indicates that composting is preferred across all four criteria. The preference for composting technology is largely due to its widespread current use, both individually and centrally. However, significant improvements are necessary, including the development of more centralized composting systems to enhance material recovery and community use of compost. Currently, compost is less favoured by farmers because its impact on plant productivity is not as strong as that of synthetic fertilizers. Therefore, enhancing the composting management system is essential.

Considering the continuous increase in waste production, particularly organic waste, it is imperative that composting technology accelerates the decomposition process beyond the capabilities of current methods. The existing composting capacities are markedly insufficient when compared to the rate of waste generation. Moreover, a significant proportion of compost products do not meet established quality standards, leading to diminished interest in their utilization. It is essential to enhance institutional and governance capacities to promote the intensification of composting within TPS3R, which currently predominates composting practices in Bali. Additionally, the integration of composting facility development into the regional development plan strategy is crucial. Furthermore, the establishment of an effective waste collection system is necessary to ensure the segregation of organic waste from other waste types.

Policy Implications

Furthermore, the results of this study align with various MCDM-based investigations in organic waste management, which underscore the significance of incorporating community-based composting and Black Soldier Fly (BSF) larvae cultivation within decentralized waste management systems. This strategy has demonstrated not only environmental sustainability but also efficacy in generating local employment opportunities (Paul & Paul 2021, Madonsela et al. 2024). Conversely, incentive policies such as tax breaks and grants for startups, coupled with capacity-building programs, can expedite technology adoption and secure sustained community support (Achmad et al. 2023). Additionally, the production of eco-enzymes-a straightforward yet highly participatory method-warrants further exploration, particularly for implementation in educational institutions, cooperatives, and rural areas as a direct community empowerment initiative. Cooperatives, especially those involved in environmental awareness and local economic development, offer structured networks and shared resources that can support the adoption of eco-enzyme production. This model of collaboration has proven effective, as seen in a community service program in Pojok Village, Kediri, East Java, Indonesia, where partnerships with the local waste bank successfully empowered residents-primarily housewives-through participatory training to turn organic waste into eco-enzyme products, leading to increased environmental awareness and waste reduction (Prodyanatasari et al. 2024).

Study Limitations

This study was conducted with input from six expert participants. Although their subject-matter expertise contributed to reliable and informed judgments, the relatively small and homogeneous sample may limit the generalizability of the findings. Incorporating a broader panel of stakeholders-such as private sector representatives, community organizations, and policymakers-would provide a more comprehensive perspective on the feasibility and acceptance of each technology. Furthermore, the economic evaluation relied solely on expert scoring rather than empirical cost data or detailed cost-benefit analyses, which diminishes the precision of financial comparisons across alternatives. Future studies should incorporate real-world cost data and apply robust economic modeling techniques. Additionally, this research did not include a life cycle assessment (LCA), which is essential for evaluating the full environmental impacts of each treatment option. The absence of LCA, combined with the potential for bias in subjective expert scoring, underscores the need for more data-driven, multi-dimensional evaluation frameworks in future research.

CONCLUSIONS

This study identifies composting, Black Soldier Fly (BSF) processing, and eco-enzyme production as the most suitable organic waste treatment technologies for Bali Province. Bioconversion methods demonstrably outperform thermal alternatives across environmental, social, and economic dimensions. Composting consistently ranks highest due to its adaptability, community acceptance, and environmental benefits, while BSF processing offers significant revenue potential and job creation opportunities. Sensitivity analysis confirms the robustness of these rankings under various stakeholder priorities.

For policy implications, decentralized composting and BSF systems should be prioritized, supported by incentives, training, and pilot projects for eco-enzyme initiatives. Broader stakeholder inclusion, integration of life cycle assessment, and empirical cost analysis are recommended for future evaluations to strengthen the evidence base and guide sustainable waste management strategies.

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