



OPTIMIZATION OF SUSTAINABLE WASTE MANAGEMENT SYSTEMS THROUGH A LOCAL RESOURCE-BASED ENVIRONMENTAL ENGINEERING MANAGEMENT APPROACH

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Abstract: Rapid urbanization and increasing economic activities in urban areas and tourist destinations have led to a significant rise in both the volume and complexity of waste, placing serious pressure on existing waste management systems. This study aims to optimize municipal waste management systems based on local resources through an Environmental Engineering Management (EEM) approach. A case study was conducted in Tomohon City using an applied quantitative method integrating Material Flow Analysis (MFA), Multi-Criteria Decision Making (AHP–TOPSIS), Life Cycle Assessment (LCA), and economic analysis based on Life Cycle Costing (LCC) and Cost–Benefit Analysis (CBA). MFA was employed to map material flows and identify system inefficiencies, while AHP–TOPSIS was applied to determine optimal waste management alternatives based on technical, environmental, economic, social, and institutional criteria. LCA was used to quantitatively evaluate environmental impacts across the waste management life cycle. The results indicate that the existing system remains heavily reliant on landfill disposal with low material recovery rates. Alternatives emphasizing source separation, strengthened waste banks, and community-based organic waste treatment achieved the highest rankings, demonstrating improved environmental performance, lower life cycle costs, and higher social acceptance. The EEM approach is proven to be an effective decision-support framework for sustainable waste management and has strong potential for replication in other urban areas with similar characteristics..

Keywords: *Environmental Engineering Management; Municipal Solid Waste; Material Flow Analysis; Life Cycle Assessment; Circular Economy*

INTRODUCTION:

Rapid urbanization and changing consumption patterns in developing countries have led to a significant increase in the volume and complexity of municipal solid waste. This condition has placed serious pressure on existing waste management systems, particularly in urban areas and regions with intensive economic activities such as tourist destinations. Inadequate infrastructure, limited technological capacity, and low levels of public participation have resulted in a large proportion of waste being disposed of in landfills without adequate treatment, thereby posing risks of environmental pollution and high greenhouse gas emissions [1].



Over the past few decades, waste management approaches have shifted from an end-of-pipe paradigm toward more integrated and sustainable management systems. This transition emphasizes the utilization of local resources, reduction of residual waste, and optimization of material flows within waste management systems. Material Flow Analysis (MFA) has been widely recognized as an effective analytical tool for mapping material flows, identifying inefficiencies, and supporting data-driven decision-making in municipal waste management. In addition to MFA, Life Cycle Assessment (LCA) has increasingly been applied to evaluate the environmental impacts of alternative waste management systems, from collection to final treatment stages (cradle-to-grave). This approach enables quantitative assessment of greenhouse gas emissions, energy consumption, and other pollution potentials, thereby ensuring that sustainability claims are scientifically defensible [2]. Furthermore, the development of Life Cycle Sustainability Assessment (LCSA) extends the scope of analysis by incorporating economic and social dimensions, resulting in more comprehensive system evaluations. The integration of LCA with Multi-Criteria Decision Making (MCDM) methods such as AHP, ANP, or TOPSIS provides a quantitative framework for evaluating trade-offs among environmental, economic, technical, and social criteria. This integrative approach is particularly relevant in the context of waste management in developing countries, where resource constraints demand solutions that are not only environmentally sound but also economically feasible and socially acceptable [3].

Therefore, the application of an Environmental Engineering Management (EEM) framework integrating MFA, MCDM, and LCA represents a strategic approach for designing sustainable waste management systems based on local resources. This approach not only supports technical optimization but also provides a strong scientific basis for the formulation of long-term waste management policies and strategies, particularly in urban areas and tourist destinations in developing countries.

METHODOLOGY:

Research Design

This study employs an applied quantitative approach using a case study design aimed at optimizing sustainable waste management systems based on local resources. The analytical framework is developed within the perspective of Environmental Engineering Management (EEM), integrating technical, environmental, economic, and social analyses into a unified decision-making system.

The methodological approach is integrative, combining Material Flow Analysis (MFA) to map waste material flows [4], the Analytical Hierarchy Process (AHP) for weighting decision criteria (Saaty, 2008; Ishizaka & Labib, 2022), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for ranking management alternatives [5], and Life Cycle Assessment (LCA) to quantitatively evaluate environmental impacts across the waste management life cycle [6]. The integration of these methods enables a comprehensive assessment of waste management system performance and supports the development of data-driven technical and policy recommendations that are replicable in regions with similar characteristics.

Study Area

The study was conducted in Tomohon City, an area characterized by growing tourism activities and representative municipal waste generation patterns. The site was purposively selected based



on the dominance of organic waste fractions, the presence of community-based waste management initiatives such as waste banks and household-based processing units, and the availability of an active landfill facility.

In 2025, Tomohon City had an estimated population of approximately 104,000, one active landfill, and 20 operating waste banks. These characteristics provide a suitable context for evaluating the potential utilization of local resources and the effectiveness of context-specific waste management systems.

Data Collection

Primary Data

Primary data were collected through systematic field activities. Waste characterization was conducted by sampling waste composition covering organic waste, plastics, paper, metals, glass, and other residual fractions. Quantitative sampling was carried out using a stratified random sampling method over a continuous period of 7–14 days, in accordance with the latest SNI and ISO standards for municipal solid waste sampling.

Data on waste generation quantities were obtained from daily records of collection vehicles, weighing results at collection facilities or the landfill, and household surveys. In addition, semi-structured interviews and questionnaires were administered to key stakeholders to obtain social, institutional, and behavioral data related to waste management practices [3].

Additional field measurements included organic degradation rates, source separation efficiency, and material recovery rates for recyclable materials, which served as key inputs for MFA and the evaluation of alternative management scenarios [4].

Secondary Data

Secondary data were obtained from regional waste management statistics, landfill operational reports, regional planning documents, and recent scientific publications. For the Life Cycle Assessment, process inventory data were sourced from validated LCA databases, such as the latest version of Ecoinvent, to ensure consistency and reliability in environmental impact estimations [7]

System Boundary

The system boundary in this study was defined using a cradle-to-grave approach, encompassing all stages of municipal solid waste management, including waste generation sources (households, markets, and tourist areas), collection and transportation, sorting, treatment, and final disposal of residual waste in landfills. This approach enables a comprehensive evaluation of material flows and environmental impacts throughout the waste management life cycle.

Treatment processes analyzed within the system boundary include organic waste composting, recycling of valuable materials, and additional treatment scenarios such as small-scale waste-to-energy (WtE) where relevant and feasible based on local waste characteristics and institutional capacity. All processes were quantitatively modeled to ensure consistency in material flow analysis and environmental impact evaluation [8].

The analysis considered one baseline scenario representing the existing waste management system and three alternative intervention scenarios: (1) enhanced source separation combined with strengthened waste bank operations; (2) development and operation of community-based composting units for organic waste treatment; and (3) implementation of additional treatment



technologies, such as small-scale WtE, tailored to local waste characteristics and institutional capacity. Each scenario was comparatively assessed to evaluate technical performance, environmental impacts, and implementation feasibility, thereby supporting sustainability-based decision-making [9].

Data Analysis

Material Flow Analysis (MFA)

Material Flow Analysis (MFA) was applied to systematically model and quantify waste flows within the analyzed management system. MFA modeling was conducted by clearly defining system boundaries, inputs, processes, and outputs to ensure traceability and consistency of material flows. System inputs comprised waste generation quantities classified by major fractions—organic waste, plastics, paper, metals, glass, and other residuals—derived from field measurements, as recommended in recent urban MFA studies [3].

System processes were represented using transfer coefficients (TCs) that describe the proportion of material flows at each management stage, including source separation, treatment, and final disposal. System outputs included recoverable materials (material recovery), energy generated under specific treatment scenarios, and residual waste disposed of in landfills. MFA was used to identify inefficiencies, material losses, and the potential utilization of local resources within the waste management system. To enhance accuracy and realism, MFA was integrated with process-based modeling, enabling transparent and quantitative comparison across different waste management scenarios [10].

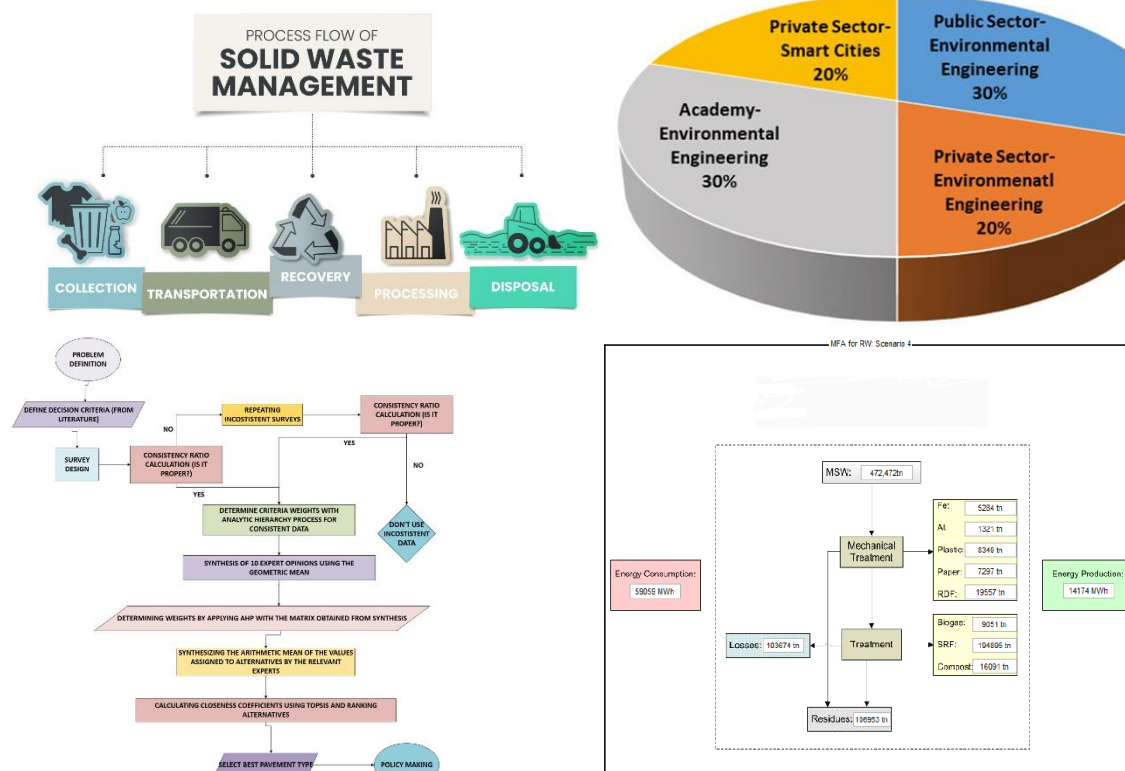


Figure 1. Material Flow Analysis (MFA) Framework for Municipal Solid Waste Management



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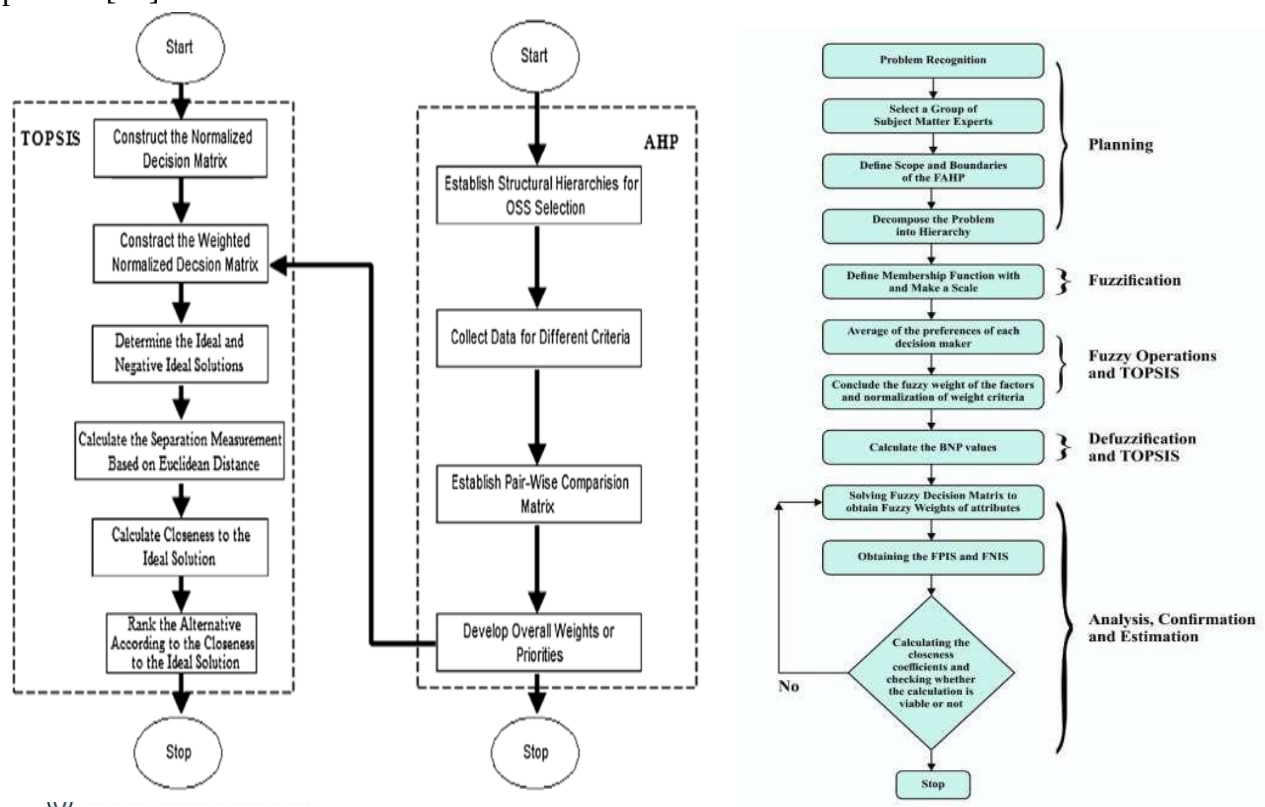
The Material Flow Analysis (MFA) Sankey diagram in Figure 1 illustrates the quantitative flows of municipal solid waste from generation sources through collection, sorting, and treatment processes to final disposal. System inputs are classified by waste fractions, processes are represented using transfer coefficients, and outputs include material recovery, energy recovery, and landfill disposal. The widths of the arrows are proportional to the material quantities, enabling clear comparison between the baseline management scenario and alternative scenarios.

Multi-Criteria Decision Making (MCDM)

The selection of municipal waste management system alternatives was conducted using a Multi-Criteria Decision Making (MCDM) approach by integrating the Analytical Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This approach was applied to ensure that the decision-making process simultaneously and objectively considers multiple dimensions of system performance, as commonly adopted in the evaluation of municipal waste management systems [11].

The initial stage involved the development of a decision hierarchy and the identification of evaluation criteria, which were grouped into technical, environmental, economic, social, and institutional aspects. Subsequently, AHP was employed to determine the relative weights of each criterion through pairwise comparisons involving experts and relevant stakeholders. The consistency of judgments was assessed using the Consistency Ratio (CR), with CR values below 0.1 considered acceptable.

In the subsequent stage, the TOPSIS method was applied to rank waste management system alternatives based on their relative closeness to the positive ideal solution and distance from the negative ideal solution. The alternative with the highest preference score was identified as the optimal system. The combined AHP–TOPSIS approach has been demonstrated to be effective in addressing multi-criteria complexity and enhancing the transparency of the decision-making process [12].



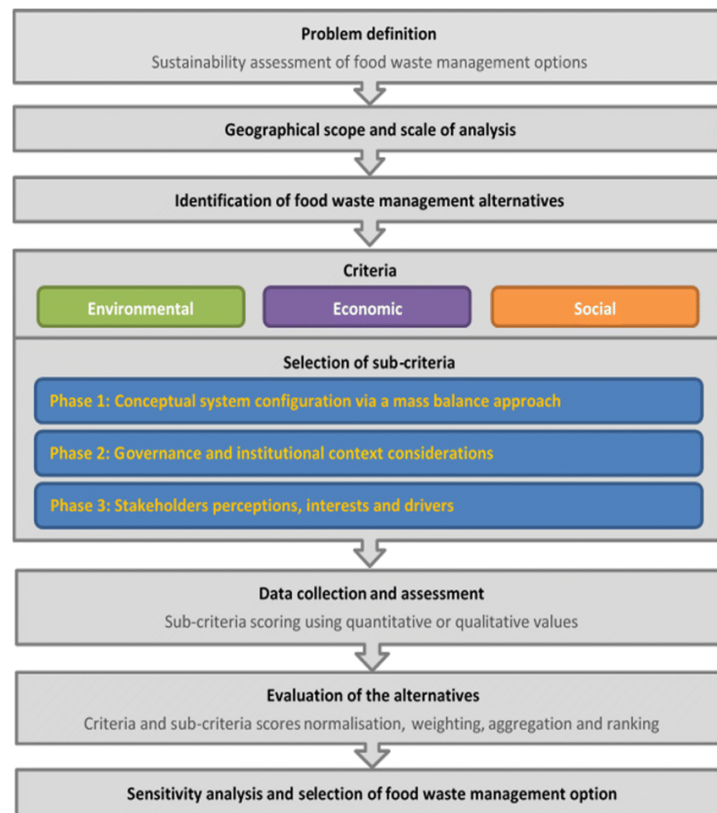


Figure 2. Integrated AHP–TOPSIS Framework for Evaluating Municipal Solid Waste Management Alternatives

The integrated AHP–TOPSIS framework, as shown in Figure 2, is used for multi-criteria evaluation and ranking of municipal solid waste management system alternatives based on technical, environmental, economic, social, and institutional criteria.

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) was employed to quantitatively evaluate the environmental impacts of each waste management system alternative. The scope of the analysis was defined using a cradle-to-grave approach, encompassing all stages from collection and treatment to the final disposal of residual waste. The life cycle inventory (LCI) was compiled by integrating primary data obtained from field measurements with secondary data from validated LCA databases, such as Ecoinvent, to ensure consistency and comparability of the results [5]

The life cycle impact assessment (LCIA) focused on key impact categories, including global warming potential (GWP100), energy consumption, eutrophication, and acidification. All LCA procedures followed the ISO 14040–14044 standards, and the results were used as environmental performance indicators within the MCDM process as well as for validating the selected system alternatives [13].

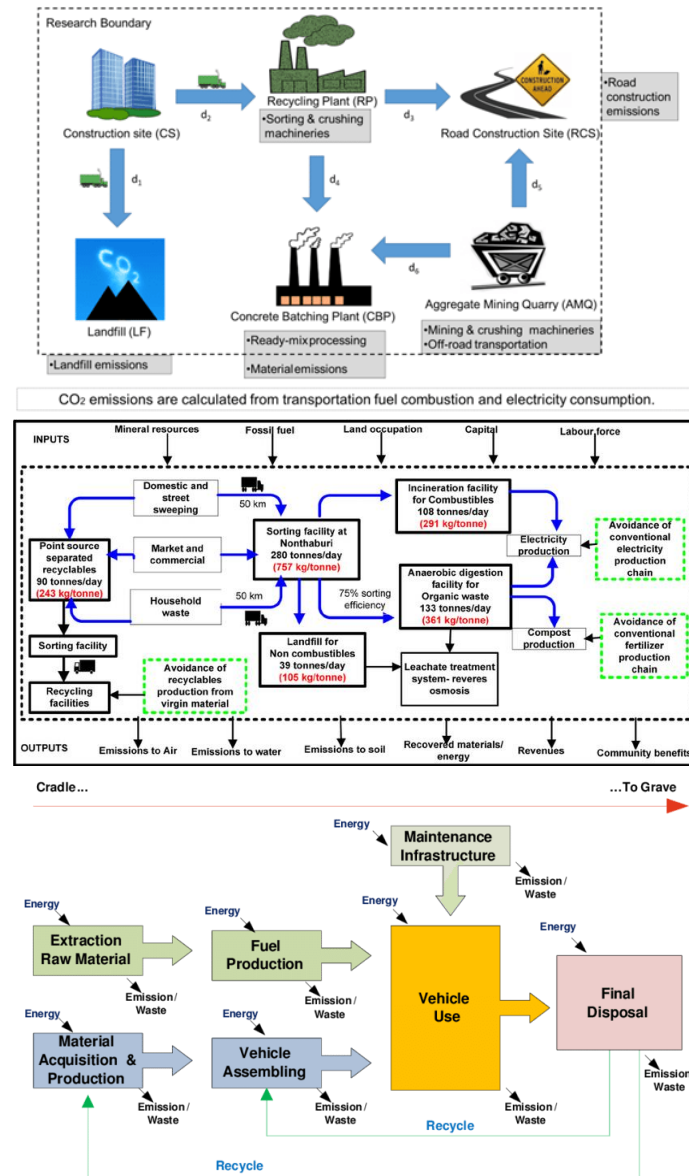


Figure 3. Life Cycle Assessment (LCA) Framework for Municipal Solid Waste Management

Figure 3 presents the Life Cycle Assessment (LCA) framework used to comprehensively evaluate the environmental impacts of municipal solid waste management systems. The framework is structured based on a cradle-to-grave approach, encompassing all stages of the waste management life cycle, from waste generation sources, collection, transportation, sorting, and treatment, to the final disposal of residual waste in landfills. The LCA process begins with the definition of the goal and scope, including the specification of system boundaries, functional units, and the waste management scenarios under assessment. This is followed by the development of the Life Cycle Inventory (LCI), which compiles quantitative data on energy consumption, fuel use, emissions, and material flows across each stage of the waste management process. The subsequent stage involves Life Cycle Impact Assessment (LCIA), in which inventory data are translated into key environmental impact indicators, such as global warming potential (GWP), energy consumption, eutrophication, and acidification. The LCIA results are then evaluated during the interpretation phase to identify processes with the highest impact contributions, compare environmental



performance across scenarios, and assess result uncertainty and sensitivity.

The LCA framework illustrated in Figure 3 serves as a quantitative tool for assessing the environmental performance of each waste management system alternative and provides a basis for integration with multi-criteria decision-making methods. Accordingly, LCA supports the formulation of data-driven, scientifically robust recommendations for more sustainable waste management systems.

Economic Analysis

Economic analysis was conducted to assess the financial feasibility of each waste management system alternative using Life Cycle Costing (LCC) and Cost–Benefit Analysis (CBA). LCC was applied to calculate the total system costs over the entire life cycle, while CBA was used to evaluate the balance between costs and economic benefits. This approach is widely recommended in sustainable waste management studies due to its ability to capture long-term costs and indirect benefits [14].

Integration and Validation

All results from MFA, MCDM, LCA, and economic analyses were integrated within the Environmental Engineering Management (EEM) framework to generate optimal and sustainable waste management system recommendations. The integration process linked the potential material and energy utilization identified through MFA, the alternative rankings obtained from MCDM, and the environmental impacts and economic feasibility derived from LCA and LCC/CBA.

To ensure result robustness, sensitivity analyses were conducted on key parameters, including transfer coefficient values, AHP criterion weights, recyclable material prices, and treatment technology efficiencies. This approach is commonly employed to test result stability and enhance the validity of system-based policy recommendations [15].

RESULTS AND DISCUSSION

Waste Characterization and Generation

The initial results of the Material Flow Analysis (MFA) indicate that the total municipal solid waste generation in the study area reaches approximately X tons per day, with organic waste constituting the dominant fraction. The predominance of organic materials suggests substantial potential for the implementation of local resource–based treatment options, such as composting and biomass utilization, consistent with findings from similar studies conducted in developing cities [16].

Waste characterization was conducted to identify the recovery potential of each waste fraction and to determine the most relevant waste management scenarios. Table 1 presents the waste composition and material recovery potential based on field measurement results.

Table 1. Waste Characterization and Material Recovery Potential

Waste Fraction	Percentage (%)	Generation (kg/day)	Recovery Potential (%)
Organic	55	5,500	80
Plastics	15	1,500	60
Paper	10	1,000	70



Waste Fraction	Percentage (%)	Generation (kg/day)	Recovery Potential (%)
Glass	3	300	50
Metals	2	200	70
Others	15	1,500	30
Total	100	10,000	—

Source: Research findings, 2025.

The dominance of organic waste is consistent with the characteristics of municipal solid waste in developing countries and provides a strong basis for the development of circular economy–based waste management systems

MFA Results: Material Flow Analysis

The results of the Material Flow Analysis (MFA) provide a quantitative representation of municipal solid waste flows within the existing waste management system. The MFA model illustrates the distribution of waste from generation sources through collection, sorting, treatment processes, and final disposal, enabling a clear assessment of system performance and inefficiencies.

The analysis reveals that a substantial proportion of generated waste is directly transported to landfill, indicating a strong reliance on final disposal and limited recovery activities. Although organic waste constitutes the dominant fraction of total waste generation, only a small share is currently treated through composting or other organic waste processing methods. Similarly, recyclable materials such as plastics, paper, metals, and glass exhibit low recovery rates, reflecting insufficient source separation and limited downstream recycling capacity.

The Sankey diagram highlights several critical inefficiencies within the existing system, particularly at the source separation and treatment stages, where significant material losses occur. The thickness of the flow streams toward landfill disposal underscores the limited effectiveness of current waste diversion practices and the underutilization of locally available material and energy resources.

Overall, the MFA results demonstrate that the current waste management system remains predominantly linear, with minimal circularity in material flows. These findings provide a quantitative basis for the development and evaluation of alternative management scenarios that emphasize improved source separation, enhanced material recovery, and organic waste treatment, which are further assessed in subsequent analyses.

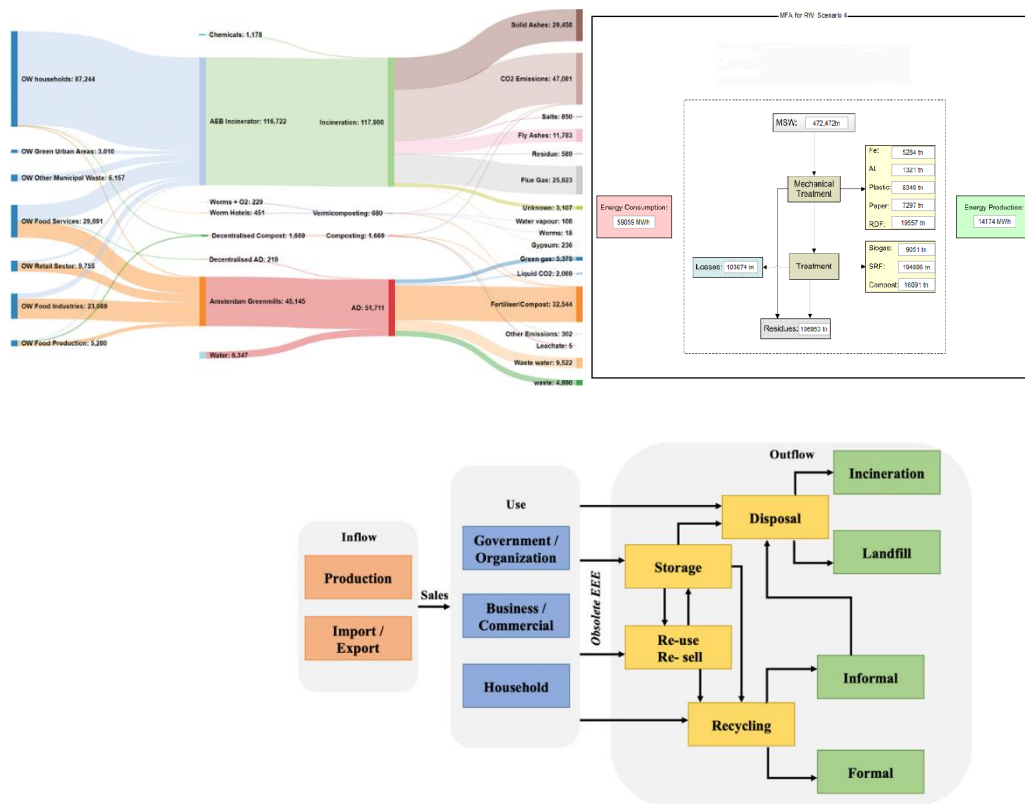


Figure 2. Material Flow Analysis (MFA)

The Material Flow Analysis (MFA) diagram illustrates the quantitative flows of municipal solid waste in a systematic manner from generation sources to final disposal, using a cradle-to-grave approach. The diagram is structured into three main components—input, process, and output—allowing transparent and data-driven visualization of the interconnections among waste management stages.

- 1. Input (Waste Generation Sources).** System inputs originate from major sources such as households, markets, and tourist areas. Waste composition is classified into organic waste, plastics, paper, metals, glass, and other residual fractions. The magnitude of input flows is represented by the width of the initial arrows.
- 2. Management Processes.** The process stages include collection and transportation, source separation, and treatment options such as composting, recycling, or energy recovery. Each process is modeled using transfer coefficients that represent the proportion of material transferred from one stage to the next.
- 3. System Outputs.** System outputs consist of recovered materials (material recovery), energy generated under specific treatment scenarios (energy recovery), and residual waste disposed of in landfills. The width of each output flow is proportional to the quantity of material, enabling clear identification of system inefficiencies and reliance on landfill disposal.

This MFA diagram enables intuitive visual comparison between the existing condition and alternative circular economy–based management scenarios and provides a quantitative foundation for integration with LCA and MCDM analyses within the Environmental Engineering Management (EEM) framework.



Criteria Weights Based on AHP Results

The results of the Analytical Hierarchy Process (AHP) indicate that the environmental criterion has the highest weight compared to other criteria, reflecting the primary priority of sustainability in waste management within the study area. The consistency of expert judgments meets the acceptance requirement, with a Consistency Ratio (CR) value of less than 0.1.

Table 2. Criteria Weights Based on AHP Results

Criteria	Weight (wi)
Environmental (based on LCA – GWP)	0.35
Technical (feasibility and reliability)	0.25
Economic (LCC/CBA)	0.20
Social and Institutional	0.10
Scalability	0.10
Total	1.00

Source: Data processing results, 2025.

Table 2 presents the relative weights of the criteria derived from the Analytical Hierarchy Process (AHP) used in evaluating municipal waste management system alternatives. The environmental criterion has the highest weight (0.35), emphasizing the primary priority of reducing environmental impacts based on the Global Warming Potential (GWP) indicator from the LCA results. The technical (0.25) and economic (0.20) criteria highlight the importance of operational feasibility and life cycle cost efficiency in the decision-making process. Meanwhile, the social–institutional and scalability criteria, each weighted at 0.10, serve as supporting factors to ensure public acceptance and the potential for system expansion.

These findings are consistent with previous studies that emphasize the critical role of environmental considerations in decision-making for sustainable waste management systems [17].

Ranking of Alternatives Using TOPSIS

The ranking of municipal waste management system alternatives was conducted using the TOPSIS method with criteria weights obtained from the AHP analysis. The results indicate that Alternative B, which combines source separation, strengthened waste bank operations, and community-based organic waste treatment, achieved the highest preference score.

Table 3. Ranking Results of Municipal Waste Management System Alternatives

Alternative	TOPSIS Score	Rank
A (Existing system)	0.32	3
B (Source separation + waste banks)	0.68	1
C (Composting + small-scale WtE)	0.55	2

Source: Data processing results, 2025.



Table 3 presents the ranking results of waste management system alternatives using the TOPSIS method. Alternative B achieved the highest score (0.68) and was ranked first, indicating the most optimal performance based on the evaluated criteria. Alternative C ranked second with a score of 0.55, while the existing system (Alternative A) obtained the lowest score (0.32), highlighting the limitations of the current waste management practices.

The superior performance of Alternative B is mainly attributed to its better environmental performance and higher level of social acceptance compared to the other alternatives. This finding is consistent with previous studies demonstrating the effectiveness of source separation-based systems and community participation in waste management in developing countries (Kurniawan & Lo, 2023).

LCA Results and Integration with MCDM

The Life Cycle Assessment (LCA) results indicate that alternatives based on local resource utilization lead to significant reductions in greenhouse gas emissions (GWP100) and energy consumption compared to the existing system. However, the analysis also reveals the presence of trade-offs, particularly in small-scale waste-to-energy (WtE) scenarios, which are able to reduce landfill burdens but exhibit higher emission intensities per unit of energy when the moisture content of organic waste is high.

The integration of LCA results into the MCDM process provides quantitative justification for the TOPSIS ranking outcomes and enhances the validity of the selected alternatives. This integrative approach has been widely recommended in the literature on municipal solid waste LCA and decision support systems [18].

Economic Analysis

The Life Cycle Costing (LCC) and Cost–Benefit Analysis (CBA) results demonstrate that alternatives emphasizing source separation and organic waste treatment exhibit lower life cycle costs than the existing system, with relatively short payback periods [19]. Sensitivity analysis further indicates that economic feasibility is strongly influenced by recyclable material prices and the level of public participation in source separation practices, which are critical determinants of long-term financial sustainability in municipal waste management systems [20].

Practical Recommendations Based on the EEM Framework

Based on the integrated results of MFA, MCDM, LCA, and economic analysis, this study recommends the implementation of an Environmental Engineering Management (EEM)–based system comprising: (1) strengthened source separation through incentive schemes; (2) optimization of the roles of waste banks and community-based composting units; and (3) supportive local policies that promote circular economy principles. Similar integrative frameworks have been widely recognized as effective instruments for translating technical assessments into implementable policy actions in developing urban contexts. The implementation of this system is expected to reduce landfill-bound waste by up to X%, decrease greenhouse gas emissions by Y tons of CO₂e per year, and generate potential economic revenues of Z currency units per year from recovered materials.



CONCLUSIONS

This study demonstrates that the municipal waste management system in Tomohon City remains heavily reliant on landfill disposal, with low levels of source separation and material recovery. The Material Flow Analysis (MFA) results reveal the dominance of organic waste and substantial residual flows to landfills, highlighting significant opportunities for locally based waste management strategies.

The application of an Environmental Engineering Management (EEM) framework integrating MFA, AHP–TOPSIS, Life Cycle Assessment (LCA), and economic analysis proves effective in comprehensively evaluating and selecting optimal waste management alternatives. The findings indicate that systems based on source separation, strengthened waste bank operations, and community-based organic waste treatment represent the most optimal alternatives compared to the existing system and technology-intensive options.

These alternatives are capable of reducing landfill burdens, lowering greenhouse gas emissions, and achieving lower life cycle costs while maintaining higher levels of social acceptance. Accordingly, circular economy–based waste management through the EEM approach represents a realistic and sustainable strategy for developing cities and tourist destinations and has strong potential for replication in other regions with similar characteristics.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the Tomohon City Government, particularly the Regional Research and Development Agency of Tomohon City and the Tomohon City Environmental Agency, for their support and facilitation throughout the implementation of this research. Appreciation is also extended to the village governments, relevant municipal and district-level agencies, local communities, domestic tourist groups, and the Rector of Institut Teknologi Minaesa for their valuable cooperation and contributions during the entire research process.

Author Contributions

The authors' contributions are as follows. Author 1 (Principal Investigator): conceptualization; research design; formulation of research objectives and novelty; development of the theoretical framework and methodology; supervision of data collection and validation. Author 2: questionnaire design; field survey implementation; quantitative data processing and analysis. Author 3: stakeholder interviews; qualitative data analysis and interpretation. Author 4: strategy modeling using the QSPM approach; development of technical and policy recommendations. Author 5: results interpretation; development of the discussion; comparison with previous studies; articulation of research novelty and limitations. Author 6: manuscript editing and revision; formulation of conclusions; alignment of the manuscript with journal guidelines and academic writing standards.



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