Municipal Solid Waste Management in San Francisco, Cebu, Philippines Using Fuzzy DEMATEL-AHP-TOPSIS

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ABSTRACT

The primary issue facing the municipality of San Francisco, Cebu, Philippines, is the treatment of Municipal Solid Waste (MSW); failure to do so would divert attention from the tourism sector, which is the municipality's primary source of income. Thus, this study covers the identification of sustainable waste treatment through ranking using fuzzy AHP and TOPSIS as well as the cause-and-effect factors of municipal solid waste management using fuzzy DEMATEL. In this study, various commonly used municipal solid waste alternatives and factors are investigated. Five waste alternatives are selected such as anaerobic digestion, composting, incineration, recycling, and landfill and the solid waste management factors are technical, socio-cultural, cost, environmental, land required, and time required. The findings in fuzzy DEMATEL show that the environmental and land requirement are the effect factors in solid waste management, while the technical, sociocultural, cost, and time requirements are the cause factors. Anaerobic digestion ranked first, composting came in second, and recycling came in third. These results show that the most sustainable waste treatment options in fuzzy AHP and TOPSIS are based on ranking. The results of this study would be useful in prioritizing factors and choosing the most suitable plan of action for municipal solid waste management. All parties involved, such as government agencies, civic associations, and the general public, would be able to understand the various techniques and tools used in the study and hence make judgements.

Keywords: Municipal Solid Waste, Sustainability, Fuzzy, DEMATEL, AHP, TOPSIS

INTRODUCTION

Nouri's (2014) study asserts that waste management is a fundamental requirement of any society. Proper waste management should be prioritized to protect the environment from industrial pollution and lower the likelihood of hazards endangering the towns' communities. It starts with the waste produced by the different municipalities. Municipal solid waste (MSW) produced roughly 1.3 billion tons in 2011, according to the Hoornweg (2015) study, which the World Bank published, and he also stated in his research that by 2025, chance to reach 2.2 billion tons. As a result, individuals discard more waste than ever, and its composition is more complex than ever (Herva, 2015). Solid waste management faces several difficulties because of population growth, urbanization, and economic expansion (Levis, 2016). These components are the primary causes of waste generation patterns: toxicity, lifestyle, income level, and socioeconomic and cultural factors. The commonplace items people use and discard, including product packaging, paint, batteries, newspapers, and grass clippings, are called municipal solid waste, or MSW. It might include garbage generated from public, commercial, residential, and institutional parks (Ng, 2014).

Understanding solid waste management (SWM) factors and alternatives is crucial because they directly impact environmental sustainability, public health, and economic efficiency. Effective SWM practices like recycling, composting, and anaerobic digestion help reduce pollution, conserve natural resources, and lower greenhouse gas emissions (Mao et al., 2015; Zaman & Lehmann, 2018). Considering factors such as cost, socio-cultural acceptance, technical requirements, time, and land use ensures that the chosen methods are economically viable, socially accepted, and technically feasible (Brown, 2016; Medina & Salas, 2018). Balancing these elements is essential for developing sustainable SWM strategies that benefit both the environment and society.

Solid waste management (SWM) addresses environmental, economic, socio-cultural, technical, time, and land use factors. Environmentally, recycling and anaerobic digestion reduce pollution and greenhouse gas emissions (Mao et al., 2015; Zaman & Lehmann, 2011). Economically, these methods require high initial investments (Michaels, 2010). Socio-culturally, public participation and cultural attitudes significantly impact success (Brown, 2016). Technically, advanced infrastructure and expertise are necessary (Mao et al., 2015). Time-wise, composting takes months, while incineration and anaerobic digestion are faster but need continuous operation (Brown, 2016; Michaels, 2010). Land use varies, with composting and landfilling needing more space compared to incineration and recycling facilities (Hoornweg & Bhada-Tata, 2012). Balancing these factors is crucial for sustainable SWM.

Solid waste management (SWM) alternatives, such as anaerobic digestion, composting, recycling, incineration, and landfilling, each have unique benefits and challenges. Anaerobic digestion reduces greenhouse gases and produces biogas, requiring significant investment and expertise (Mao et al., 2015). Composting recycles nutrients into the soil with low costs and broad acceptance but requires months and substantial space (Brown, 2016). Recycling conserves resources and reduces pollution but depends on public participation and complex sorting facilities (Zaman & Lehmann, 2015). Incineration minimizes waste volume and generates energy but faces high costs and pollution concerns (Michaels, 2010). Landfilling is the least favored due to environmental impacts and large land requirements, despite being cost-effective initially (Hoornweg & Bhada-Tata, 2012).

San Francisco, Cebu, Philippines, is one municipality in Camotes, Cebu Islands, experiencing the fastest growth and is a second-class municipality. The island's socioeconomic activities expanded, and small-scale and other businesses were transparent daily. Fifty-nine thousand, two hundred thirty-six is the population number based on the 2020 census. Every year, the population and economic activity of the municipality of San Francisco, Cebu, grows, which may lead to a rise in waste generation. Based on current data, the population average annual growth rate is 1.9% higher than the growth rate of Cebu City, which is 1.6%. The area is estimated to be 41.29 square miles. The management of solid waste and how to deal with the growing amount of waste is one issue the San Francisco municipality is facing.

For this reason, they currently run various solid waste management programs. Their current Approach to solid waste management is another alternative to the landfill with an environmentally friendly SWM option. They currently use composting and anaerobic digestion as alternatives, aside from applying the concept of the 3 R's (reduce, reuse, and recycle). However, they have yet to have a basis or plan for how these alternatives will be sustainable because there are various factors to be considered. Using this study's findings, we can develop holistic decision-making intended for municipal solid waste management by selecting the best alternative based on the different factors involved. That is why fuzzy multicriteria decision analysis is the best Approach to this problem. It aims to develop a comprehensive decision-making process and prioritize the best municipal solid waste management approach.

Consistent decision-making requires a systematic evaluation of the selection criteria. Multicriteria decision analysis, or MCDA, helps identify the multiple interventions and fixes that must be prioritized to create comprehensive decision policies for waste management. It is, therefore, essential to establish a multicriteria approach for setting priorities, particularly in settings where decisions are produced.

This study employs a variety of alternatives and fuzzy DEMATEL to determine the causal relationships between the factors to give solid waste management decision-makers an accurate foundation. With fuzzy AHP and fuzzy TOPSIS, the viable municipal solid waste management options are ranked. One of the study's gaps is that, in contrast to previous research on improving municipal solid waste management, this study will employ the fuzzy MCDA approach—a contemporary and well-liked method for analyzing the various variables and prioritizing decisions.

BACKGROUND OF THE STUDY

Theories used of the study

The theories listed below provide evidence for the need to identify the various parameters involved in the management of municipal solid waste.

Socio-ecological Approach

A *socio-ecological approach* is a framework that incorporates ecological and social aspects of decision-making. Urie Bronfenbrenner created this in the 1970s, and it is frequently used by Ghosh (2021) to examine the intricate interactions between people, communities, and the environment regarding waste management. This method is a valuable tool for Multicriteria Decision Analysis (MCDA), a technique for evaluating alternatives in decision-making that consider multiple criteria. Stovpets (2020) discussed through his study that the socio-ecological Approach can assess the sustainability of solid waste treatment techniques, such as recycling, composting, and landfilling. According to this theory, waste management is a complex system of interactions among ecological, social, and economic elements. It emphasizes the importance of comprehending and controlling these interactions to manage waste sustainably.

Studies have shown that this model implies structural, functional, and managerial intervention in the waste generation process and is applied in analyzing waste recycling strategies (Ghosh, 2021). Environmental sociologists advance several strands of analysis that specifically articulate interactions and discuss the relationship between humans and their environments, including areas of human ecology.

Waste Hierarchy

A *waste hierarchy* is an idea that assigns a waste management solution a rating based on how it will affect the environment. This theory suggests Ferrari (2016) should prioritize waste management in a hierarchy, with waste prevention being the best course of action. Preventive measures, reuse, recycling, recovery (including energy recovery), and disposal are the best options. This strategy's primary objectives are to reduce waste production and maximize resource recovery.

Waste hierarchy (WH) is a widely accepted idea that is applied in many beneficial contexts to waste management policies. It must be managed to lessen any possible harm urban solid waste may cause to the environment and public health. VanEwijk and Stegemann's (2016) circular economy concepts are likewise based on the notion that modern societies should work toward becoming zero-waste and sustainable. The WH uses the goal of diverting waste from landfills to complain about waste management, symbolized by an inverted pyramid. The primary cause of waste being diverted from landfills is more space for disposal sites. Although landfills continue to be the less expensive option, this has raised interest in alternative waste management techniques. Landfills are regarded as the best pragmatic environmental option (BPEO) in developing nations because of several factors, including low disposal costs, a lack of funding, and technological resources to enhance selective collection systems and space availability. In many European countries, landfills remain the most widely used method of disposing of waste, despite the opinions of some authors who believe they are the worst choice. This is according to the WH. The WH, which views this waste management solution as appropriate but the worst option given the circumstances, is consistent with this situation. The 3 Rs (Reduce, Reuse, Recycle) and the Waste Hierarchy are both frameworks aimed at managing waste and promoting sustainable practices, but they approach the issue from slightly different perspectives.

Rs—Reduce, Reuse, and Recycle

The *3 Rs—Reduce, Reuse, and Recycle*—form a foundational framework in sustainable waste management and environmental conservation. According to EPA (2020), this approach emphasizes minimizing waste generation, maximizing resource use, and promoting a circular economy. The concept of waste reduction stems from preventing waste generation at its source. It focuses on minimizing the consumption of resources and the production of waste materials. At the same time, reuse involves extending the life cycle of products by using them multiple times before their disposal. Recycling consists of reprocessing materials to manufacture new products, thus reducing the need for raw materials and minimizing waste. The theoretical background of recycling aligns with ecological economics, emphasizing the importance of preserving natural resources and reducing environmental impact.

Sustainable Materials Management, or SMM

Sustainable materials management, or SMM, is a systematic approach to better use goods and materials at every life cycle stage, from extraction to disposal. This outlines the method that considers the long-term impacts of products and materials on the economy, society, and environment. Reducing the environmental impact of material production, use, and disposal is crucial, according to McKay (2019).

The SMM approach changes societal attitudes regarding the conservation of the environment and the use of natural resources. New opportunities can be found to lower costs, conserve resources, and lessen environmental impact by considering a product's entire lifecycle. This theory provides a framework for managing materials and products sustainably throughout their whole lifecycle, from resource extraction to design and manufacturing, resource productivity, consumption, and end-of-life management.

Studies have shown that effective waste management is one of many critical processes for sustainability. Instead, a strategy for managing the movement of materials throughout the industrial and economic systems is needed. An organization defines sustainable materials management (SMM) as "an approach to promote sustainable materials use, integrating actions targeted at reducing negative environmental impacts and preserving natural capital throughout the lifecycle of materials, considering economic efficiency and social equity." SMM is a strategy for decoupling economic growth from the consumption of natural resources (EEA, 2019).

SMM encourages examining how a set of policies affects a specific target area, which encourages exploring policy incoherence. It aims to reduce the quantity of material that must be extracted, easing some resource-related stress. SMM promotes sustainable decision-making by balancing social, environmental, and economic factors throughout a material's life cycle. This ensures that adverse effects do not transfer from the production phase to the consumption phase or vice versa. For SMM policies to be effective, the consumption of materials and other natural resources, like energy and water, must be balanced. For instance, McKay (2019) suggests substituting bio-based, renewable materials for non-renewable ones, like petroleum derivatives, but these replacements may use more water and other ecosystem services.

These theories present a range of perspectives and methods for addressing waste management issues. Combining these theories can result in more effective and sustainable waste management techniques. Keep in mind that local contexts, laws, and resources may have an impact on how effective these theories are. The following are the planned municipal solid waste management considerations: cost, technical, land- and time-related, environmental, sociocultural, and technical requirements. These are predicated on the aforementioned theories. These elements are appropriate because they are grounded in the theories of the Socio-ecological Approach, Waste Hierarchy, 3Rs (Reduce, Reuse, and Recycle), and Sustainable Materials Management (SMM).

Factors that can affect Municipal Solid Waste Management

Environmental as Solid Waste Management Factor

Many studies have examined the environmental aspects of choosing alternatives for municipal solid waste (MSW). Multicriteria analysis was used by Herva (2013) and Medina-Salas (2017) to rank MSW treatment options. Herva concluded that thermal plasma gasification was the most helpful method, while Medina-Salas identified composting, recycling, and landfilling as the most common scenarios. Using multicriteria analysis, Antonopoulos (2014) also determined that energy recovery combined with incineration was the best method. Bovea (2010) conducted a case study in Spain to compare various MSW management strategies and discovered that multiple treatment options and selective collection can majorly impact environmental performance. Together, these studies show how crucial it is to consider various environmental factors when choosing MSW alternatives, including energy recovery and selective collection.

Cost as Solid Waste Management Factor

Other important factor to be focused was the importance of considering costs when choosing between different options for managing municipal solid waste (MSW). Cost analysis was used by both Ghinea (2016) and Medina-Salas (2017) to determine the best MSW management scenarios; Medina-Salas highlighted the importance of balancing economic and environmental costs. Zhou (2022) found that the financial input intensity of MSW management in China increased significantly, indicating a growing emphasis on cost. Fasano (2021) identified the number of rooms in residential buildings and construction years as key factors influencing MSW management costs in the Apulia region of Italy.

Socio-cultural as Solid Waste Management Factor

Many sociocultural factors influence the alternatives for managing municipal solid waste (MSW). Herva (2013) emphasizes the importance of considering environmental perspectives, while Le (2023) presents social, economic, and ecological criteria for sustainability assessment. Nguyen (2020) delves deeper into how socioeconomic shifts affect the characteristics of MSW, emphasizing the role that lifestyle, economic activity, and safety concerns play. Kourgiantakis (2020) emphasizes the need to enhance teaching methods related to culture and diversity, with simulation being a promising tool. Morris (2023) highlights the role of management in promoting tolerance, acceptance, and respect for cultural diversity in the workplace, which can lead to increased business performance.

Technical as Solid Waste Management Factor

Technical aspects play a crucial role in municipal solid waste management (MSWM) (Shanta, 2023; Bui, 2020). Shanta (2023) identifies and prioritizes key criteria for technology selection in MSWM, emphasizing the importance of access to technology, feasibility, and infrastructure requirements. Bui (2020) further underscores the significance of economic efficiency and technology in enhancing the capability of MSWM systems. These findings highlight the critical role of technical considerations in the effective management of MSW.

Land Required as Solid Waste Management Factor

The importance of land in municipal solid waste (MSW) management is underscored by several recent studies. Meena (2023) emphasizes the need for alternative waste management practices, such as recycling and composting, which require land for their implementation. Samsudin (2021) highlights the role of land-use planners in incorporating MSW management into development planning, indicating the need for designated land for waste treatment facilities. Zhou (2022) and Mor (2023) both discuss the environmental impacts of MSW landfills, with Mor (2023) specifically noting the significant land area required for these facilities. These studies collectively underscore the critical role of land in MSW management, from waste treatment to landfilling, and the need for sustainable land use practices in this context. Appropriate landfill sites through multicriteria decision analysis based on geographic information systems. These studies highlight the importance of considering groundwater depth, surface water proximity, elevation, land slope, soil permeability, and proximity to urban areas when choosing disposal sites for municipal solid waste.

Time Required as Solid Waste Management Factor

The time required for MSW management is a crucial factor in the field of social work, as it is linked to positive health outcomes (Rowe, 2019). However, the specific importance of time in this context is not explicitly addressed in the other studies. Wu (2019) and Kusmaul (2020) both provide valuable insights into the broader field of social work and stormwater management, respectively, but do not directly discuss the time required for MSW management. Similarly, while Farrukh (2021) offers a comprehensive overview of the Chinese Management Studies, it does not delve into the specific role of time in MSW management. Therefore, while the time required for MSW management is undoubtedly important, further research is needed to fully understand its significance.

Alternatives for treating solid waste

Waste management can process waste to produce clean energy. Every homeowner and business owner in the world needs to understand waste management. Waste management includes efficiently disposing of goods and materials that are no longer required. In San Francisco, they use anaerobic, recycling, and landfills, which are the current MSWM alternatives. However, many methods are employed worldwide, such as pyrolysis, anaerobic digestion, recycling, composting, incineration, and waste to energy (Demirbas, 2011). We need a set of criteria and potential substitutes for our TOPSIS, DEMATEL, and fuzzy AHP analyses. The information gathered from the San Francisco agencies handling solid waste is used to determine feasibility. The following treatment options were selected for further consideration based on their viability in San Francisco:

Anaerobic digestion

Anaerobic digestion is a promising technology for the treatment of organic waste in solid waste management (Kumar, 2020). It has the potential to not only treat waste but also generate renewable energy in the form of methane. However, there are challenges in its widespread implementation, including poor methane yield and process instability. Despite these challenges, there is a growing trend in the use of anaerobic digestion facilities in life cycle assessments of solid waste management (Mulya, 2022). This trend reflects the increasing recognition of the potential of anaerobic digestion in waste management. To further enhance the performance of anaerobic digestion, there is a need for research on feedstock pre-treatment and process optimization (Ampese, 2021). These studies collectively highlight the potential of anaerobic digestion in solid waste management and the need for further research to improve its efficiency and effectiveness.

Incineration

Incineration is a popular method for managing municipal solid waste (MSW) due to its ability to destroy waste and its cost competitiveness (Theodore, 2021). However, the treatment of incineration residues, particularly fly ash, is a significant challenge due to their high heavy metal and soluble salt content (Kanhar, 2020). Various treatment technologies have been developed to address this issue, including thermal treatment, stabilization/solidification, and resource recovery (Zhang, 2021). In India, the Ministry of Environment, Forests and Climate Change has introduced new Solid Waste Management Rules, 2016, which include incineration as one of the waste treatment methods (Meena, 2023).

Composting

Composting is a key component of sustainable solid waste management (SWM) in urban areas, particularly in developing countries like India and Colombia (Maturi, 2022; Machado, 2020). It is a low-cost and environmentally friendly option that can significantly reduce the volume of waste sent for final disposal (Meena, 2023). However, the successful implementation of composting programs requires adequate space, stakeholder engagement, and contingency plans to mitigate potential threats (Machado, 2020). Despite its potential, the adoption of composting in SWM systems is still limited, with only a small percentage of MSW being recycled through composting in India (Meena, 2023). Therefore, further research and policy support are needed to promote the widespread use of composting as a SWM treatment.

Landfills

Ritter (2024) provides a comprehensive overview of the history of landfill and landfill gas management in the United States, highlighting the significant role of landfills in solid waste management. Ghosh (2023) emphasizes the need for better global landfill management practices, particularly in the context of reducing methane emissions and their impact on the environment. Premsudha (2022) underscores the environmental and health impacts of landfill pollution, particularly in developing countries like India. Vinti (2021) further supports these concerns, identifying increased risks of adverse birth and neonatal outcomes, mortality, respiratory diseases, and negative mental health effects associated with residing near landfills. These studies collectively underscore the importance of effective landfill management in solid waste management, particularly in mitigating environmental and health risks.

Recycling

Recent research has highlighted the importance of recycling in solid waste management (SWM) treatment. Renã (2021) and Meena (2023) both emphasize the need for technological and organizational innovations in SWM, with Renã specifically noting the transformational impact of waste recycling. Abis (2020) and Iqbal (2020) further underscore the potential of recycling in improving SWM, with Abis calling for increased recycling quotas and Iqbal advocating for the integration of recycling, treatment, and disposal technologies. These studies collectively highlight the critical role of recycling in sustainable SWM treatment.

Fuzzy DEMATEL

Fuzzy Decision-Making Trial and Evaluation Laboratory (Fuzzy DEMATEL) is an advanced multi-criteria decision-making (MCDM) method that integrates fuzzy logic with the traditional DEMATEL approach, enhancing the ability to handle uncertainties and ambiguities inherent in human judgment and decision-making processes. The classical DEMATEL method, developed by the Battelle Memorial Institute in the 1970s, is designed to visualize the structure of complex causal relationships through matrices and directed graphs, and is particularly useful for identifying and analyzing the influence and interdependencies among factors within a system. Fuzzy DEMATEL extends this methodology by incorporating fuzzy set theory, which was introduced by Lotfi Zadeh in the 1960s. The Decision Making Trial and Evaluation Laboratory (DEMATEL) method is a structural modeling technique used to establish causal relationships between ideas produced by expert decision-makers through the division of the variables (e.g., barriers of UTT in this case) into causal and impact groups (Büyük€ ozkan & Çifçi, 2012; Kahraman et al., 2015).This integration allows for the representation of vague and imprecise information, enabling more nuanced and flexible modeling of human perceptions and expert opinions. In Fuzzy DEMATEL, linguistic variables and fuzzy numbers are used to express the strength of relationships between factors, making it possible to capture the uncertainty and subjectivity in expert evaluations more effectively. Key features of Fuzzy DEMATEL include its ability to handle uncertainty by using fuzzy logic, which addresses the imprecision and subjectivity in expert judgments, providing a more accurate representation of real-world complexities. It also helps in constructing a cause-effect relationship model among factors, enabling decision-makers to understand the interdependencies and influence levels within a system. The results are often visualized through directed graphs, making it easier to interpret the structure and dynamics of the relationships.

Table 1. List of Municipal Solid Waste Management Factors

MSWM Factors	References
1 Technical	Shanta (2023), Bui (2020)
2 Socio-cultural	Herva (2013), Le (2023), Nguyen (2020), Kourgiantakis (2020), and Morris (2023)
3 Cost	Ghinea (2016), Medina-Salas (2017), Zhou (2022), and Fasano (2021)
4 Environmental	Herva (2013), Medina-Salas (2017), Antonopoulos (2014), and Bovea (2010)
5 Land Required	Meena (2023), Samsudin (2021), Zhou (2022), and Mor (2023)
5 Time Required	Rowe (2019), Wu (2019), Kusmaul (2020), and Farrukh (2021)

Fuzzy AHP

The Analytic Hierarchy Process (AHP) is a popular multi-criteria decision-making (MCDM) method developed by Thomas L. Saaty in the 1970s. It is used for organizing and analyzing complex decisions, allowing decision-makers to model a problem in a hierarchical structure and quantify its various elements based on their relative importance. However, traditional AHP often struggles to handle the inherent uncertainty and vagueness present in human judgment. To address this limitation, Fuzzy AHP (FAHP) was introduced, incorporating fuzzy logic into the AHP framework. Fuzzy AHP enhances the conventional AHP by using fuzzy numbers instead of exact numerical values to represent the pairwise comparisons between criteria and alternatives. This approach allows for a more realistic modeling of uncertainty and imprecision, reflecting the way humans naturally think and make decisions. A series of recent studies have explored the application and development of Fuzzy Analytic Hierarchy Process (FAHP). Castelló-Sirvent (2022) conducted a bibliometric analysis, identifying thematic clusters and collaboration networks in FAHP research. Liu (2020) reviewed FAHP methods for decision-making, categorizing techniques and providing guidance for their selection. Zhang (2021) compared AHP and FAHP methods, focusing on their transformation of linguistic judgments.

Fuzzy TOPSIS

TOPSIS is a multiple criteria method to identify solutions from a finite set of alternatives and initially proposed by Chen and Hwang (1992). The underlying logic of TOPSIS proposed by Hwang and Yoon (1981) is to define the ideal solution and negative ideal solution. The optimal solution should have the shortest distance from the positive ideal solution and the farthest from the negative ideal solution. If to remind, human judgments were rely on imprecision, subjectivity and vagueness; so they address fuzzy logic. Here evaluations expressed by linguistic terms and then set into fuzzy numbers. Recent research has explored the application of Fuzzy TOPSIS in various decision-making scenarios. Gündogdu (2020) used the method to select optimal sites for electric vehicle charging stations, while University (2021) compared its performance with other methods in supplier selection. Sharif (2021) proposed a novel fuzzy entropy measure to enhance the method's effectiveness in decision-making, particularly in the context of the COVID-19 pandemic. Mathew (2020) further extended the method by integrating it with AHP under spherical fuzzy sets, demonstrating its robustness in advanced manufacturing system selection. These studies collectively highlight the versatility and potential of Fuzzy TOPSIS in addressing complex decision-making problems.

Table 2. List of Solid Waste Treatment

Solid Waste Treatment	References
1 Anaerobic Digestion	Kumar (2020), Mulya (2022), and Ampese (2021)
2 Incineration	Theodore (2021), Kanhar (2020), Meena (2023) and Zhang (2021)
3 Composting	Maturi (2022), Machado (2020), and Meena (2023)
4 Landfill	Ritter (2024), Ghosh (2023), Premsudha (2022), and Vinti (2021)
5 Recycling	Renã (2021), and Abis (2020)

Table 3. Criteria in selecting the expert decision-makers

1 Expertise Background and Expertise	Relevant Qualifications: Experts should have academic degrees in fields such as environmental science, engineering, public health, waste management, or related disciplines. Specialized Training: Additional certifications or training specifically related to solid waste management can be an asset.
2 Professional Experience	**Industry Experience:** Extensive experience working in waste management, including roles in planning, implementation, and evaluation of waste management programs. **Project Management:** Demonstrated experience managing projects related to waste collection, recycling, disposal, and treatment facilities.
3 Technical Knowledge	**Solid Waste Technologies**: In-depth understanding of technologies used in waste collection, recycling, composting, and disposal (e.g., landfill management, waste-to-energy technologies). **Environmental Impact:** Knowledge of the environmental impacts of various waste management practices and methods to mitigate these impacts.
4 Regulatory Knowledge	**Legal Framework:** Familiarity with local, national, and international regulations governing waste management.

	Compliance and Standards: Understanding of compliance requirements and industry standards for waste management practices.
5 Leadership and Decision-Making Abilities	**Strategic Planning**: Proven track record of strategic planning and policy development in the waste management sector. **Ethical Decision-Making**: Commitment to ethical practices and transparency in decision-making processes.

Case of the solid waste management in San Francisco, Cebu, Philippines

Study Area

The Municipality of San Francisco, in the Province of Cebu, was the study's location. San Francisco, a third-class municipality, is one of the islands' municipalities that is growing fastest. The socioeconomic activities of the island were expanding, and small businesses and other enterprises were commonplace. Fifty-nine thousand two hundred thirty-six people called this municipality home as of the 2020 census. The Province of Leyte in the Camotes Sea borders San Francisco in the north; the island and town of Poro border it on the east; the Camotes Sea borders it to the south; and the Camotes Sea borders it to the east. San Francisco, Cebu, is one municipality on the Camotes Islands, growing the fastest in population and economic activity. San Francisco is divided into 15 barangays in terms of politics. There are puroks in every barangay, and some also have sitios. Pacijan, also known as Pajican, and Tulang, located immediately north of Pacijan and occupying less than one square kilometer (0.39 sq mi), are the two main islands that make up San Francisco. These islands are part of the Poro, Ponson, and Camotes Islands. They are located east of the main island of Cebu, south and west of Leyte, and north of Bohol. Pacijan Island is approximately 14.75 kilometers (9.17 miles) long and 8.5 kilometers (5.3 miles) wide. A causeway spanning 1,400 meters (1,530 yards) connects the islands of Pacijan and Poro, passing over a mangrove swamp. It was built as a bridge between the islands during the Spanish era to encourage trade and church attendance at Poro.

METHODOLOGY

Both qualitative and quantitative research methods were used in the study. Key informant interviews and secondary research gathered information about San Francisco, Cebu's social and environmental context, including the options for waste collection and management in the municipality, to find out the current state of solid waste management practice. The first step in the data collection process involved gathering all the information on solid waste management, including SWM alternatives, processes, policies, and other related details in San Francisco and Cebu. The second step involved using the MCDA approach to determine the causal relationship between the various SWM factors and rank the alternatives for prioritization, following the identification of the current SWM practice. The evaluation of waste was done through quantitative and qualitative analysis. The criteria were chosen and identified, and numerical scores representing the preference scale for each choice for each criterion were assigned. The study identified 12 participants, including the chosen staff members of the Solid Waste Management (SWM) office in San Francisco, Cebu, Philippines, who had more than 10 years of the said position, as well as municipal and barangay officials in San Francisco, Cebu, who were involved in the planning and implementation related activities for solid waste management and qualified for the given criteria.

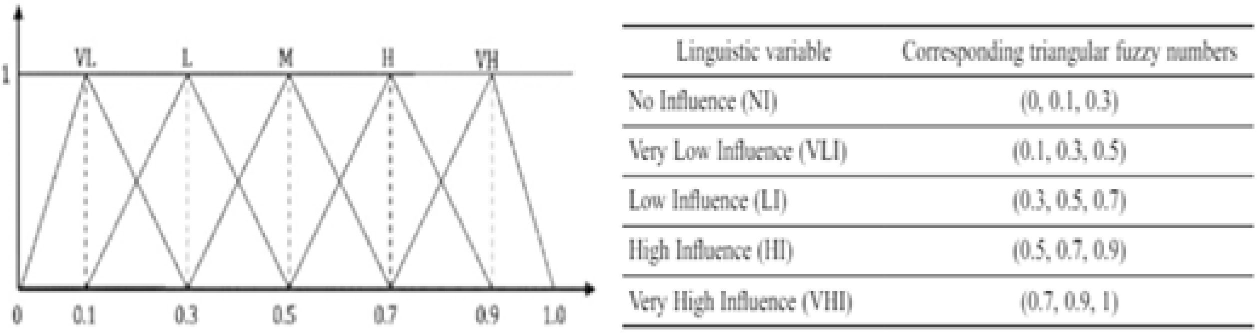
The first stage of data collection involves gathering relevant information about the current process by interviewing people and scanning documents. Then, the fuzzy MCDA approach was applied for the final phase of data collection. The proponents distribute research questionnaires based on the linguistic scale of the different fuzzy methods. The context of fuzzy DEMATEL identifies the causal relationships among the different criteria, while fuzzy AHP and fuzzy TOPSIS concentrate on identifying the ranking of the factors and the ranking of the MSWM alternatives. For fuzzy DEMATEL questionnaire, Cost (a), sociocultural (b), environmental (c), technical (d), land required (e), and time required (f) were the six dimensions included in the fuzzy-DEMATEL questionnaire. The questionnaires were the primary recipients of the Solid Waste Management (SWM) office, a group of experts, and SWM board members with ten years of service experience. The ambiguity of the experts' subjective assessments was considered during the survey. A linguistic description method was used to guarantee that the evaluation values of the experts' subjective judgments were appropriately expressed. Next, each judgment value was converted into a fuzzy triangle and assigned a 5-point rating to indicate its level of influence. For fuzzy DEMATEL, the influence was ranked as VH, H, L, VL, or NO while for fuzzy AHP and TOPSIS, the fuzzy TOPSIS and AHP aims to determine the ranking of MSWM alternatives in San Francisco and Cebu. Anaerobic digestion (AD), incineration (IC), composting (CP), landfill (LF), and renewable energy (RW) are the five options that have been identified. Cost (a), cost sociocultural (b), environmental (c), technical (d), land required (e), and time required (f) are the six benefit criteria that are taken into account. The questionnaires were mainly given to specialists, and the ambiguity was resolved using a linguistic scale. On a scale of 1 to 0, 0 represents very low, and 1 means excellent (VL, L, M, H, VH, E). This relates to the linguistic variables for each criterion's importance weight, whereas for the linguistic variables used in the ratings, ten is very good, and 0 is very poor (VP, P, MP, F, MG, G, VG).

RESULTS

Fuzzy DEMATEL

Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) is a method used to analyze and understand complex relationships among various factors in a system. It helps in determining the degree of influence and dependence between these factors. Here’s a step-by-step guide on how to apply fuzzy DEMATEL:

Step 1: Compute average initial direct- relation matrix (Matrix A). In this study, we apply the triangular fuzzy number and use the linguistic scale and its corresponding fuzzy numbers which are defined by Chen (2000). Tseng (2009) also used Chen’s (2000) study for the linguistic scale and its corresponding fuzzy numbers. Figure 7 shows used fuzzy numbers dealing with each expert response. Expert’s assessment of facility pair with respect to each considered factors should be converted fuzzy numbers into crisp scores. This process named defuzzification. In this study, “Converting the Fuzzy data into Crips Scores” (CFCS) method (developed by Tzeng 2003) is employed for the defuzzification process.



Linguistic variable	Corresponding triangular fuzzy numbers
No Influence (NI)	(0, 0.1, 0.3)
Very Low Influence (VLI)	(0.1, 0.3, 0.5)
Low Influence (LI)	(0.3, 0.5, 0.7)
High Influence (HI)	(0.5, 0.7, 0.9)
Very High Influence (VHI)	(0.7, 0.9, 1)

Figure 1. Fuzzy DEMATEL Linguistic scales for the importance weight of criteria

CFCS method includes following four steps. These steps are given as follows based on Tseng (2009).

- Normalization

$$\left.\begin{array}{l}\Delta_{\min}^{\max} = \max a_{3ij}^{k} - a_{1ij}^{k} \\ xa_{1ij}^{k} = (a_{1ij}^{k} - \min a_{1ij}^{k}) \,/\, \Delta_{\min}^{\max} \\ xa_{2ij}^{k} = (a_{2ij}^{k} - \min a_{1ij}^{k}) \,/\, \Delta_{\min}^{\max} \\ xa_{3ij}^{k} = (a_{3ij}^{k} - \min a_{1ij}^{k}) \,/\, \Delta_{\min}^{\max}\end{array}\right\}. \qquad (1)$$

- Compute left(ls) and right(rs) normalized values:

$$\left.\begin{aligned} xls_{ij}^{k} &= (xa_{2ij}^{k}/(1+xa_{2ij}^{k}-xa_{1ij}^{k}) \\ xrs_{ij}^{k} &= (xa_{3ij}^{k}/(1+xa_{3ij}^{k}-xa_{2ij}^{k}) \end{aligned}\right\}. \tag{2}$$

- Compute total normalized crisp value:

$$x_{ij}^{k} = [xls_{ij}^{k}(1-xls_{ij}^{k}) + xrs_{ij}^{k}xls_{ij}^{k}]\,/\,[1-xls_{ij}^{k}+xrs_{ij}^{k}], \tag{3}$$

- Compute crisp values:

$$w_{ij}^{k} = \min a_{1ij}^{k} + x_{ij}^{k}\,\Delta_{\min}^{\max}. \tag{4}$$

Table 4. Fuzzy DEMATEL Aggregated Triangular Fuzzy Number for Experts

	Cost (a)			**Socio-cultural (b)**			**Environmental ©**			**Technical (d)**			**Land Required (E)**			**Time Required (f)**		
Cost (a)	1	1	1	0.3	0.67	0.9	0.5	0.7	0.9	0.5	0.86	1	0.5	0.84	1	0.3	0.58	0.9
Socio-cultural (b)	0.3	0.6	1	1	1	1	0.1	0.67	0.9	0.1	0.6	0.9	0.1	0.65	1	0.1	0.5	0.9
Environmental ©	0.3	0.67	0.9	0.1	0.68	1	1	1	1	0.1	0.53	0.9	0.5	0.82	1	0.1	0.6	0.9
Technical (d)	0.5	0.89	1	0.1	0.57	0.9	0.3	0.63	1	1	1	1	0.1	0.67	1	0.3	0.67	0.9
Land Required (e)	0.7	0.91	1	0.3	0.63	1	0.3	0.78	1	0.1	0.6	1	1	1	1	0.1	0.65	0.9
Time Required (f)	0.3	0.6	1	0.1	0.53	0.9	0.1	0.62	1	0.3	0.63	0.9	0.1	0.65	1	1	1	1

Step 2: Compute the normalized initial direct-relation matrix (Matrix D) by using equation (5) and (6).

$$S = \max\left(\max_{1<i<n}\sum_{j=1}^{n} a_{ij}, \max_{1<j<n}\sum_{i=1}^{n} a_{ij}\right), \tag{5}$$

$$a_{ij} = (1/H)\ x \sum_{k=1}^{H} x_{ij}^{k}. \tag{6}$$

Step 3: Compute factor total-influence matrix (Matrix T) by using equation (7).

Table 5. The Prominence and Relation Axis for Cause-and-Effect Group

	a	**b**	**c**	**d**	**e**	**f**	**D**	**R**	**D+R**	**D-R**	**Category**
Cost (a)	2.818	2.469	3.531	2.424	2.953	2.475	16.669	16.640	33.309	0.029	net cause
Socio-cultural (b)	2.644	2.241	3.285	2.267	2.763	2.294	15.493	14.356	29.848	1.137	net cause

Environmental (c)	2.968	2.561	3.699	2.519	3.075	2.599	17.421	20.734	38.154	-3.313	net effect
Technical (d)	2.695	2.324	3.345	2.287	2.807	2.397	15.855	14.244	30.098	1.611	net cause
Land Required (E)	2.834	2.456	3.557	2.432	2.943	2.518	16.741	17.349	34.090	-0.608	net effect
Time Required (f)	2.681	2.305	3.318	2.314	2.808	2.318	15.744	15.744	31.488	0.000	net cause
R	16.640	14.356	20.734	14.244	17.349	14.600	97.923	97.923			
Threshold Value	**2.720**										

I = identity matrix

$$T=D(I-D)^{-1} \qquad (7)$$

Step 4: Set a threshold value to filter out minor effects and Compute C, R, C + R, and R – C values to obtain diagram of showing causal relations among criteria. If values are less than threshold value, the values in matrix T are reset to zero. The basic notations to conduct this step are given as follows:

C = sum of column of the matrix T,

R = sum of row of the matrix T,

$r_i + c_j$= the importance of factor i,

$r_i – c_j$ = the net effect of factor i.

Table 5. The Prominence and Relation Axis for Cause-and-Effect Group

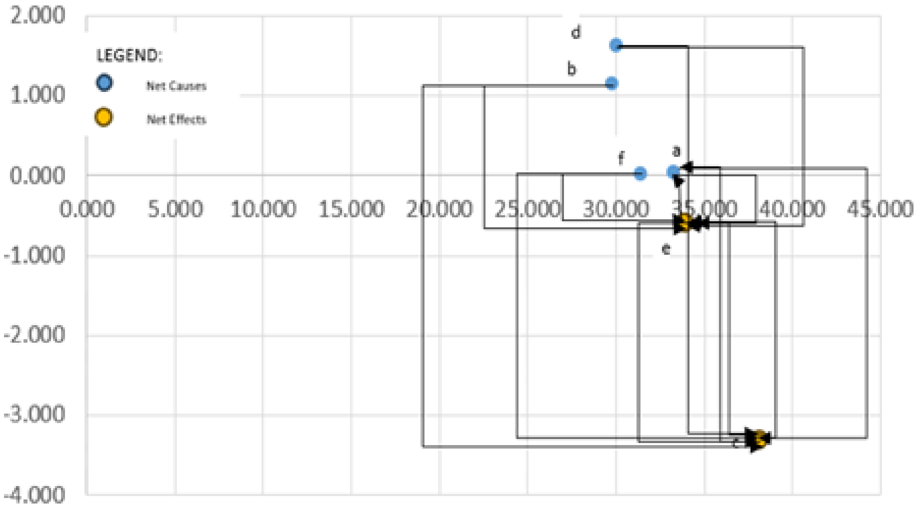
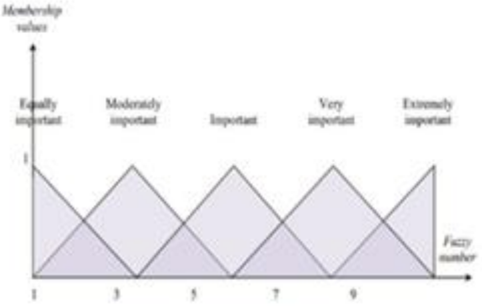


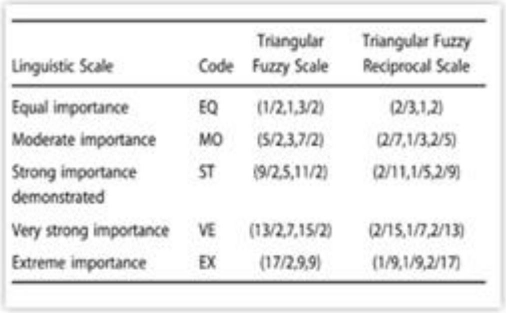
Figure 2. Fuzzy DEMATEL Impact Relationship Map

Fuzzy AHP

Thomas L. Saaty developed the Analytical Hierarchy Process (AHP) in the 1970s to facilitate decision-making. The FAHP improves the AHP. AHP solves challenging decision-making problems by arranging the criteria and options into a hierarchical model and comparing them pairwise to determine their relative importance.

Step 1. AHP uses several small sub-problems to present a complex decision problem. Thus, the first act is to decompose the decision problem into a hierarchy with a goal at the top, criteria and sub-criteria at levels and sub-levels and decision alternatives at the bottom of the hierarchy





Linguistic Scale	Code	Triangular Fuzzy Scale	Triangular Fuzzy Reciprocal Scale
Equal importance	EQ	(1/2,1,3/2)	(2/3,1,2)
Moderate importance	MO	(5/2,3,7/2)	(2/7,1/3,2/5)
Strong importance demonstrated	ST	(9/2,5,11/2)	(2/11,1/5,2/9)
Very strong importance	VE	(13/2,7,15/2)	(2/15,1/7,2/13)
Extreme importance	EX	(17/2,9,9)	(1/9,1/9,2/17)

Figure 3. Fuzzy AHP Linguistic variables for the ratings (Saaty, 1996)

Table 6. Fuzzy AHP Experts' Perception

	Cost			**Socio-cultural**			**Environmental**			**Technical**			**Land Required**			**Time Required**		
Cost	1	1	1	1/7	5 5/7	9	1/9	2 4/9	9	1/9	1/6	1	1/9	1 5/7	9	1/9	1 1/7	9
Socio-cultural	1/9	1	7	1	1	1	1/9	1 5/8	7	1/9	3/4	9	1/9	8/9	7	1/7	1 1/6	7
Environmental	1/9	4 2/9	9	1/7	4 1/4	9	1	1	1	1/9	3 4/5	9	1/9	1 1/2	9	1/9	3	9
Technical	1	6 1/3	9	1/9	5 3/7	9	1/9	1 4/5	9	1	1	1	1/7	5 3/7	9	1/9	3 1/3	9
Land Required	1/9	4 1/2	9	1/7	4	9	1/9	3 4/5	9	1/9	5/8	7	1	1	1	1/9	4 1/8	9
Time Required	1/9	4 6/7	9	1/7	3 1/5	7	1/9	2 2/3	9	1/9	2 2/5	9	1/9	1 3/5	9	1	1	1

Step 2. The comparison matrix involves the comparison in pairs of the elements of the constructed hierarchy. The aim is to set their relative priorities with respect to each of the elements at the next higher level.

$$D = \begin{array}{c} \\ C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_n \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & C_2 & C_3 & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & x_{13} & \cdots & x_{1n} \\ x_{21} & x_{22} & x_{23} & & x_{2n} \\ x_{31} & x_{32} & x_{33} & & x_{3n} \\ \vdots & & & & \\ x_{n1} & x_{n2} & x_{n3} & & x_{nn} \end{bmatrix} \end{array} \tag{1}$$

Table 7. Fuzzy AHP Decision Matrix

	Weight	AD	IC	CP	LF	RW
Cost	**0.1263**	0.1918	0.193	0.2075	0.2031	0.2045
Socio-cultural	**0.1527**	0.1828	0.0936	0.2059	0.1937	0.2053
Environmental	**0.1838**	0.1709	0.1004	0.2066	0.1919	0.1945
Technical	**0.1854**	0.1925	0.2042	0.1854	0.2025	0.1936
Land Required	**0.176**	0.1703	0.18	0.2061	0.132	0.1939
Time Required	**0.1759**	0.1927	0.2052	0.1938	0.1802	0.2039

Step 3. AHP also calculates an inconsistency index (or consistency ratio) to reflect the consistency of the decision maker's judgments during the evaluation phase. The inconsistency index in both the decision matrix and in pairwise comparison matrices could be calculated with Eq. (2). The principal eigenvalue of the judgement matrix and n is the order of the judgement matrix. The closer the inconsistency index to zero, the greater the consistency. The consistency of the assessments is ensured if the equality holds for all criteria. The relevant index should be lower than 0.10 to accept the AHP results as consistent. If this is not the case, the decision maker should go back and redo the assessments and comparisons.

$$CI = \frac{\lambda_{\max} - N}{N - 1} \tag{2}$$

Where $\lambda_{\max}$ is the principal eigenvalue of the judgement matrix and n is the order of the judgement matrix. The closer the inconsistency index to zero, the greater the consistency. The consistency of the assessments is ensured if the equality $(a_{ij}a_{jk} = a_{ik}, \forall i, j, k)$ holds for all criteria. The relevant index should be lower than 0.10 to accept the AHP results as consistent. If this is not the case, the decision maker should go back and redo the assessments and comparisons

Table 8. Fuzzy AHP Consistency Ratio

Consistency Ratio				
Weight	**V**	**λ max**	**CI**	**CR**
0.18309	0.1282	5.4	0.1	0.0833
0.1628	0.117			
0.20035	0.0859			
0.18295	0.0768			
0.19879	0.03			

Step 4. In the next step, transform the real elements of matrix R into the fuzzy numbers.

Step 5. Before conducting all the calculation of vector of priorities, the comparison matrix D has to be normalized by Eq. (2).

Step 6. To find the criteria weights, calculate the average of the elements of each row from matrix obtained from step 4.

Table 9. Fuzzy AHP Ranking Table

Ranking Table					
	AD	IC	CP	LF	RW
Cost	0.0242	0.0244	0.0262	0.0257	0.0258
Socio-cultural	0.0279	0.0143	0.0315	0.0296	0.0313
Environmental	0.0314	0.0185	0.038	0.0353	0.0357

Technical	0.0357	0.0379	0.0344	0.0375	0.0359
Land Required	0.03	0.0317	0.0363	0.0232	0.0341
Time Required	0.0339	0.0361	0.0341	0.0317	0.0359
TOTAL	**0.1831**	**0.1628**	**0.2003**	**0.183**	**0.1988**
Rank	**3**	**5**	**1**	**4**	**2**

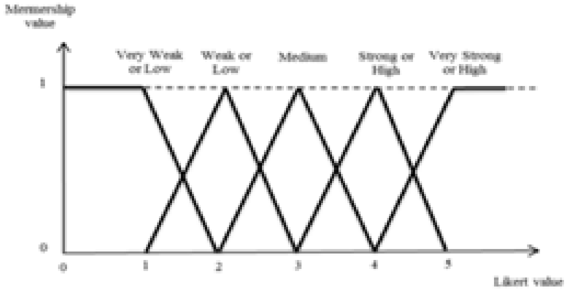
Fuzzy TOPSIS

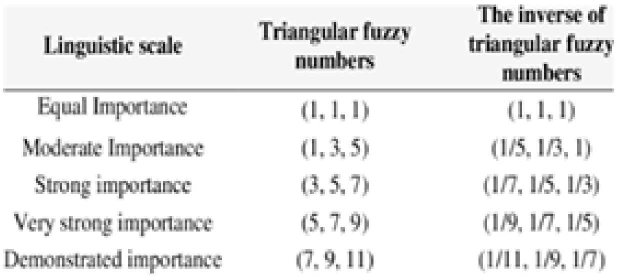
An MCDM technique called Fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) builds on the classic TOPSIS approach to improve decision-making processes in the face of imprecision and uncertainty. When making decisions, it is helpful to have the options and criteria represented as fuzzy numbers.

The basic steps In the Fuzzy TOPSIS process are:

Step 1: Determine the weighting of evaluation criteria. This research employs fuzzy AHP to find the fuzzy preference weights.

Step 2: Construct the fuzzy performance/decision matrix and choose the appropriate linguistic variables for the alternatives with respect to criteria





Linguistic scale	Triangular fuzzy numbers	The inverse of triangular fuzzy numbers
Equal Importance	(1, 1, 1)	(1, 1, 1)
Moderate Importance	(1, 3, 5)	(1/5, 1/3, 1)
Strong importance	(3, 5, 7)	(1/7, 1/5, 1/3)
Very strong importance	(5, 7, 9)	(1/9, 1/7, 1/5)
Demonstrated importance	(7, 9, 11)	(1/11, 1/9, 1/7)

Figure 4. Fuzzy TOPSIS Linguistic variables for the ratings (Huang & Lin, 2006)

$$\widetilde{\boldsymbol{D}} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \end{array}$$

$$i = 1, 2, \ldots,\ m; j = 1, 2, \ldots, n$$

$$\tilde{x}_{ij} = \frac{1}{K}\left(\tilde{x}_{ij}^{1} \oplus \cdots \oplus \tilde{x}_{ij}^{k} \oplus \cdots \oplus \tilde{x}_{ij}^{K}\right) \tag{1}$$

Table 10. Fuzzy TOPSIS Expert's Perception

	Cost (a)			**Socio-cultural (b)**			**Environmental (c)**			**Technical (d)**			**Land Required (e)**			**Time Required (f)**		
AD	0.3	0.73	1	0.3	0.7	1	0.3	0.78	1	0.3	0.75	1	0.3	0.65	0.9	0.3	0.68	1
IC	0.5	0.87	1	0.1	0.5	1	0.1	0.53	1	0.1	0.8	1	0.3	0.7	1	0.3	0.7	1

CP	0.1	0.53	1	0.3	0.78	1	0.3	0.82	1	0	0.27	0.7	0.5	0.83	1	0.3	0.82	1
LF	0.5	0.83	1	0.1	0.6	1	0	0.48	1	0	0.33	1	0.3	0.87	1	0.1	0.62	1
RW	0.1	0.58	1	0.3	0.73	1	0.1	0.6	1	0.1	0.47	0.9	0.3	0.67	1	0.3	0.67	1

Step 3: Normalize the fuzzy-decision matrix. The normalized fuzzy-decision matrix denoted by R is shown as following formula:

$$\tilde{\boldsymbol{R}} = [\tilde{r}_{ij}]_{m\times n}, \quad i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n \tag{2}$$

Step 4: Determine the fuzzy positive-ideal solution (FPIS) and fuzzy negative-ideal solution (FNIS). According to the weighted normalized fuzzy-decision matrix, we know that the elements v ~ij are normalized positive TFN and their ranges belong to the closed interval [0,1]. Then, we can define the FPIS A+ (aspiration levels) and FNIS A (the worst levels) as following formula:

$$\begin{aligned} A^{+} &= (\tilde{v}_1^{*}, \ldots, \tilde{v}_j^{*}, \ldots, \tilde{v}_n^{*}) \\ A^{-} &= (\tilde{v}_1^{-}, \ldots, \tilde{v}_j^{-}, \ldots, \tilde{v}_n^{-}) \end{aligned} \tag{3}$$

Table 11. Fuzzy TOPSIS Distance from FPIS

Distance from FPIS							**di***
AD	0.060	0.021	0.011	0.016	0.095	0.033	0.236
IC	0.000	0.072	0.094	0.041	0.071	0.029	0.306
CP	0.138	0.000	0.000	0.222	0.012	0.000	0.371
LF	0.011	0.047	0.113	0.164	0.041	0.050	0.425
RW	0.125	0.013	0.073	0.123	0.081	0.037	0.451

Step 5: Calculate the distance of each alternative from FPIS and FNIS. The distances of each alternative from A+ and A can be currently calculated by the area compensation method

$$\begin{aligned} \tilde{d}_i^{+} &= \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^{*}\right), \quad i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n \\ \tilde{d}_i &= \sum_{i=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j\right), \quad i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n \end{aligned} \tag{4}$$

Table 12. Fuzzy TOPSIS Distance from FNIS

Distance from FPIS							**di-**
AD	0.078	0.051	0.103	0.209	0.000	0.018	0.459
IC	0.138	0.000	0.020	0.214	0.044	0.022	0.438

CP	0.000	0.072	0.113	0.000	0.086	0.050	0.320
LF	0.129	0.025	0.000	0.124	0.086	0.000	0.364
RW	0.017	0.059	0.039	0.107	0.041	0.015	0.278

Step 6: Obtain the closeness coefficients (relative gaps-degree) and improve alternatives for achieving aspiration levels in each criterion.

Table 13. Fuzzy TOPSIS Ranking Table

di*	**di-**	**Cci**	**Rank**	**Alternatives**
0.236	0.459	0.660716	1	Anaerobic Digestion
0.306	0.438	0.588992	2	Incineration
0.371	0.320	0.46317	3	Composting
0.425	0.364	0.461225	4	Landfill
0.451	0.278	0.380894	5	Recycling

DISCUSSIONS AND IMPLICATIONS

Fuzzy DEMATEL

The threshold value, 2.720, which is the average of the total relation matrix is shown in the table. The values above the threshold (highlighted in red) (> 2.720) in table 5 are those factors that has a significant effects or influence, according to the threshold values. The values of D+R (x axis) & D-R (y axis) are additional results from the table. Furthermore, there are four cause factors—technical, sociocultural, cost, and time required—while there are two effect factors: the environment and land required. This number indicates that other system components are directly impacted by technical aspects of solid waste management. With a positive D-R value of 1.611, technical factor (d) has a significant impact on the other factors in the system. Considering the significance of technical factor in solid waste management for San Francisco, Cebu, the results of D+R and D-R of technical factor (d) suggest that it stands for a crucial component, particularly in the planning stage. The management cannot advance further without the fulfillment of technical requirements such as waste collection system, waste segregation, waste processing and treatment, technology integration, environmental control, regulatory compliance, etc. This, in turn, prevents other challenges from emerging. Essentially, resolving issues related to technical factor (d) may positively affect the resolution of other challenges or mitigate their impact. Socio-cultural (b) is another factor that contributes to net cause; it has a positive D-R value of 1.137, indicating its role in solid waste management in San Francisco as well as its relationship to other factors. Other elements in the system may be directly impacted by this factor's influence. Furthermore, the socio-cultural factor (b) has a positive D+R value of 29.848, demonstrating its substantial impact on other system components. The results of the socio-cultural factor's D+R and D-R indicate that factors like educational awareness, cultural attitudes and practices, policies and regulations, religious beliefs, community identity and values, and how waste is generated, perceived, handled, and managed within a community are crucial for managing solid waste. The socio-cultural factor (b) can also be the cause of the problem in solid waste management if not strategically handled and potential cause other challenges from occurring. Resolving socio-cultural factor related may reduce the impact of the problems in solid waste management. Similarly, Cost (a) is another factor that indicates also its relationship with other factors that has positive D-R = 0.029 and 33.309 for D+R. The results indicates that cost (a) factor is one of the cause factors that can affect the other solid waste factors such as labor cost, energy cost, transportation cost, facilities, administration and overhead cost, etc. The result of D+R and D-R value of cost (a) implies that this factor influences every aspect of solid waste management, from daily operations to long-term planning, and are essential for ensuring that waste management systems are efficient, sustainable, and acceptable to the public and other stakeholders.

Additionally, the time required (f) has a D+R of 31.488, demonstrating its strong correlation with other variables. This indicates that other factors in the system may be directly impacted by the time required factor (f). Furthermore, the time required (f) has a positive D-R value of 0.000, indicating that it significantly affects the system's other factors. This result suggests that in order to ensure that the system runs smoothly, economically, and in a way that protects the environment and public health, related activities in the time required (f), such as collection, transportation, waste generation rate, segregation and sorting, processing and treatment, disposal, etc., are essential in solid waste management. On the other hand, two factors—the environmental (c) and the land requirement factor (e)—are classified as having a net effect. The systemic factors have a significant influence on these factors, as indicated by their positive D+R and negative D-R values. These elements are frequently the results or after effects of other systemic root causes. More all-encompassing solutions that focus on the underlying causes or interdependencies with other issues may be necessary to address the net effect challenges. It is essential to comprehend the cause and effect of the relationships between the various components that make up the solid waste system in San Francisco, Cebu. Figure 8 shows the fuzzy DEMATEL Impact Relationship Map, which illustrates the causal relationships between system components and helps to clarify the interrelationships between the solid waste management factors in San Francisco, Cebu. The yellow dots represent the net effect factors (e and c), and the blue dots represent the net cause factors (a, b, d, and f). Arrows are used to show the connections between these dots; the direction and thickness of the arrows indicate the strength and direction of the influence.

This supports it even more, stating that technical, socio-cultural, cost and time required are the factors most considered as the cause criteria. These factors are part of the resources strongly supported in the several studies where it was found that these factors were also the cause criteria in solving problems. The study of Guerero (2019) shows that technical aspects such as the availability of infrastructure, technological advancements, and the efficiency of waste processing systems are crucial for effective waste management. Abbas (2020) stated the result on his study that cost associated with waste management includes expenses related to collection, transportation, processing, and disposal. Budget constraints and financial planning are essential for sustainable waste management systems. According to the study of Palanivel (2020) socio-cultural factors include public awareness, community participation, cultural attitudes towards waste, and education. These elements significantly impact how waste is generated, segregated, and managed at the community level. Another study of Zhao (2021) time considerations involves the time required for collection, transportation, processing, and final disposal of waste. Efficient time management ensures that waste does not accumulate, which can lead to environmental and health hazards. In terms of the net effect factors of the result (environmental and land required) also supported by other related studies. Proper waste management is essential for reducing greenhouse gas emissions, preventing soil and water contamination, and mitigating other ecological damages. Lifecycle assessments are often used to evaluate the environmental performance of different waste management strategies, helping to identify the most sustainable options (Istrate et al., 2020; Teixeira & Guerra, 2024). The amount of land needed for waste management facilities, particularly landfills, is a major concern. Landfills must be carefully sited to minimize their environmental footprint and to avoid conflicts with other land uses. Effective site selection involves considering factors like proximity to populations, environmental sensitivity, and potential for future land reclamation (Teixeira & Guerra, 2024; Ilyas et al., 2022).

Fuzzy AHP

According to the Fuzzy AHP results, composting, recycling and Landfill (rank first, second, and third, respectively, in terms of cost (0.2057, 0.2024 and 0.201) and the value for consistency ratio is 0.0928 which means it is consistent, sociocultural impact (0.2039, 0.2027 and 0.2009) and the value for consistency ratio is 0.0928 which means it is consistent and environmental impact (0.2052, 0.1926 and 0.1894) and the value for consistency ratio is -0.018 which means it is consistent. Regarding the technical factor, incineration (0.2027) ranks first, landfills (0.2) rank second, and recycling ranks (0.1922) third and the value for consistency ratio is 0.0958 which means it is consistent. The three factors favor for land required are composting (0.204), incineration (0.2006), and recycling (0.1918). In terms of Time Required and the value for consistency ratio is

0.0839 which means it is consistent, composting (0.2018) ranks third, recycling (0.2021) ranks second, and incineration (0.2025) ranks first. Following the computation of the decision matrix, composting (0.2001) ranks first overall, recycling (0.1968) ranks second, anaerobic digestion (0.1873) ranks third, landfill (0.1819) ranks fourth and incineration (0.1800) ranks fifth and the value for consistency ratio is 0.0833 which means it is consistent.

A range of studies have highlighted the potential of anaerobic digestion, composting, and recycling as sustainable treatment options for organic waste. Joshi (2019) and Cucina (2023) both emphasize the environmental and economic benefits of these methods, with Joshi specifically noting the preference for anaerobic digestion in Asia due to its lower energy footprint and higher public acceptance. Yaser (2022) further underscores the potential of these methods for campus sustainability, while Czekała (2023) discusses the recycling of anaerobic digestate solid fraction through composting, highlighting its value as a substrate for compost production. Iacovidou (2019) presents a framework for assessing the value of resources recovered from waste, with a strong emphasis on recycling as a primary method for achieving a circular economy. The study evaluates the environmental and economic benefits of recycling. Zhang (2020) provides a comprehensive assessment of the environmental and economic aspects of plastic waste recycling, emphasizing the sustainability benefits. These studies collectively support the use of anaerobic digestion, recycling, and composting as effective and sustainable waste management strategies.

Fuzzy TOPSIS

Based on the fuzzy TOPSIS calculation results, the options that rank first are anaerobic digestion gains (0.578868 Cci), followed by incineration gains (0.556059 Cci), composting gains (0.492058 Cci), landfill (0.337304 Cci), and recycling (0.306449), which rank fourth and fifth, respectively.

A range of studies have highlighted the potential of anaerobic digestion as a sustainable treatment for organic waste, particularly in Asia (Joshi, 2019) and Europe (Cucina, 2023). This method not only reduces the environmental and health risks associated with other treatments like incineration and landfilling (Joshi, 2019), but also offers significant energy recovery and cost benefits (Zhuang, 2022). However, the use of incineration without anaerobic digestion has been proposed as a more sustainable approach for handling excess sludge (Hao, 2019), suggesting that the choice of treatment may depend on the specific waste type and local context. Composting is a sustainable treatment for organic waste, with various technologies and methods available for its implementation. Dhamodharan (2019) highlights the importance of controlling odorous gas emissions during the composting process, with biofiltration being a successful treatment option. Makan (2020) assesses the sustainability of large-scale composting technologies, finding that reactor technologies are the most sustainable. However, Santos (2022) and Zakaria (2021) raise concerns about the environmental and social risks associated with incineration, such as air and water pollution. These concerns may have contributed to the prohibition of incineration in certain areas.

CONCLUSION

Data from the Solid Waste Management Office in San Francisco, Cebu, shows that waste generation is rising annually because of population growth and economic expansion. The solid waste management team's work is crucial in addressing this issue, particularly for decision-making. Many new techniques have emerged, and constructive research is underway to determine the most effective response to this growing threat. Fuzzy MCDA has aided the most effective SWM alternatives to employ in our study and in the development of sustainable plans. It was found that the technical, socio-cultural, cost, and time requirements are the cause factors, and the environment and land required factors are the effect factors using fuzzy DEMATEL's six criteria. Furthermore, the five alternatives were rated using six criteria in fuzzy TOPSIS and AHP; the results for these factors would yield the optimal SWM alternatives. Composting, anaerobic digestion, and recycling are the best waste treatments based on the results. Both personal research and data gathered from technical experts served as the foundation for our study. Thus, decision-makers involved in solid waste management may take into consideration the findings of the study. That is, requirement related to technical, socio-cultural, cost, and time required needed for planning and development must be given top priority while recycling, anaerobic digestion, and composting in treating waste before landfill shall be practiced and implemented. To this end, the rising waste generation will be addressed and reduced the landfill site count, thus, achieving a sustainable solid waste management in the municipality.

Declaration of competing interest

The authors declare no conflicts of interest.

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