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Research article

Evaluating sustainable municipal solid waste management scenarios: A multicriteria decision making approach

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ABSTRACT

Due to increasing urbanization and population growth, municipal solid waste management (MSWM) is a significant environmental concern in developing countries. Inadequate waste management systems lead to environmental pollution, health hazards, and economic losses. While considering the challenges and limitations, policymakers and authorities need to opt for such waste management scenarios that are environmentally friendly and resolve energy issues. Ten MSWM scenarios were developed and evaluated using seven different criteria. Four multi-criteria decision-making (MCDM) techniques, namely fuzzy logic, AHP, TOPSIS, and PROMETHEE II, were employed to rank the scenarios and identify the most appropriate option for solid waste management in Lahore. This study highlights that the optimal waste management approach comprises a composition of 54% anaerobic digestion, 37% gasification, and 9% landfill technologies. These percentages collectively represent the most suitable and effective strategies for the city's waste management needs. All the MCDM techniques consistently produce similar results. These scenarios have broader applicability across cities in Central Asia and beyond. The study's findings are aligned to promote sustainable and environmentally friendly MSWM practices. These findings endorse implementing strategies and measures aimed at fostering environmental sustainability and the responsible handling of waste, serving as a valuable reference for various regions.

1. Introduction

Climate change caused by global warming is one of the major challenges faced by the world today [1]. The issue of global warming has gained significant attention in recent years as the impact of climate change has become more apparent [2]. Many governments and

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organizations are now taking measures to reduce greenhouse gas emissions and mitigate the effects of global warming [3]. Managing municipal solid waste presents an opportunity to mitigate greenhouse gas emissions and address the global warming challenge. The implementation of sustainable waste management practices, such as the utilization of waste-to-energy technologies, can effectively mitigate the volume of waste that is deposited in landfills [4].

The waste generation has experienced a substantial rise over time, primarily attributed to population expansion and urban development. Inadequate waste management practices can result in severe environmental and health risks [5]. As per the World Bank's report, there is anticipated to be a 70% increase in global waste production by 2050, with a significant portion of the rise originating from developing nations [6]. According to estimates from 2016, worldwide annual waste production amounted to approximately 2.01 billion metric tons. Most of this waste was generated in Asia, with Europe, Africa, and North America following closely behind. By the year 2050, the aforementioned figure is projected to rise to 3.4 billion metric tons [7].

Like numerous other developing nations, Pakistan is dealing with a waste management problem. Pakistan's more than 240.5 million population results in significant daily waste production [8]. Based on estimations, Pakistan generates approximately 49.6 million tons of waste annually, mostly originating from urban regions. However, the current waste management infrastructure within the country is insufficient.

Because of insufficient collection and disposal infrastructure, a significant portion of the nation's solid waste is either incinerated or deposited in uncovered areas, contaminating the atmosphere, water, and soil [9]. The buildup of refuse in public spaces has resulted in an increase in disease-carrying insects and rodents, which contribute to transmitting diseases such as dengue fever and cholera [10]. Improper waste management has negatively influenced Pakistan's tourism industry, with numerous popular tourist destinations contaminated by litter and garbage [11]. The waste management situation in large cities in Pakistan is notably concerning. The substantial amount of waste produced in urban regions, coupled with insufficient infrastructure for collection and disposal, has led to overflowing landfills, the accumulation of garbage on streets and sidewalks, and pollution of lakes and streams.

Solid waste management is a crucial component of sustainable development due to its significant impact on people's daily lives, the environment, and the achievement of global objectives. The Sustainable Development Goals (SDGs) of the United Nations provide a comprehensive framework for addressing pressing global challenges and promoting sustainable practices. Several Sustainable Development Goals (SDGs) emphasize the significance of effective solid waste management in attaining other objectives, including sustainable urban and community development, water security, climate change mitigation, responsible consumption and production, ecosystem preservation, and health promotion.

The city of Lahore, which ranks among the largest urban centers in Pakistan, is dealing with a substantial waste management situation. The urban center has a population exceeding 13 million individuals, with projections indicating that it will produce roughly 6000 tons of waste daily in 2023 [12]. In Lahore, Municipal Solid Waste (MSW) collection primarily falls under the Lahore Waste Management Company (LWMC) jurisdiction. Currently, the waste produced in Lahore is managed through diverse methods, such as landfills, incineration, and open dumping. The city is geographically divided into various zones, each having designated collection points and schedules. Households are encouraged to segregate their waste into organic and inorganic categories, although achieving full compliance with this practice remains a significant challenge. After collection, the MSW is transported to landfill sites on the city's outskirts. LWMC manages the transportation process through a fleet of waste collection vehicles. Lahore predominantly relies on landfill disposal for its waste management. The primary landfill site, the Lakhodair landfill, has been operating for an extended period and is currently approaching its maximum capacity. Recycling initiatives in Lahore are still nascent, with informal waste pickers playing a crucial role in the recovery of recyclable materials. The current MSW management practices in Lahore blend formal and informal approaches. Despite ongoing efforts to enhance waste collection and raise public awareness, substantial challenges persist concerning landfill management, recycling, and implementing waste-to-energy initiatives. Multi-Criteria Decision-Making (MCDM) techniques can play a vital role in improving MSW management practices in Lahore. MCDM techniques provide a structured and data-driven approach to address the complex challenges of MSW management in Lahore. By considering multiple criteria and stakeholder inputs, these techniques can help make informed decisions, optimize processes, and ultimately improve the overall effectiveness and sustainability of MSW management practices in the city.

It is recommended that municipal authorities implement innovative waste management techniques that reduce the waste burden and offer sustainable solutions to address the city's energy demands. Implementing waste-to-energy (WtE) methods presents an effective way to manage the solid waste produced in Lahore effectively. These methodologies entail the conversion of garbage into beneficial energy sources, such as electrical or thermal energy [13]. There are various waste-to-energy (WtE) techniques that are employed for solid waste management, such as incineration, anaerobic digestion, gasification, hydrothermal liquefaction (HTL), refuse-derived fuel (RDF), composting, and fermentation.

The incineration process entails the combustion of waste materials at elevated temperatures, leading to the generation of thermal energy that can be harnessed for the production of electricity [14]. Gasification is a process that involves the conversion of waste into syngas, which can be utilized for electricity generation [15]. The RDF process entails converting waste materials into pellets, which can serve as a fuel source for energy generation through combustion. The process of anaerobic digestion involves using microorganisms to decompose organic waste, producing biogas that can be harnessed for the generation of heat or electricity [16]. Composting is a process that entails the biological breakdown of organic waste, resulting in the production of a soil amendment that is rich in nutrients [17]. Hydrothermal liquefaction (HTL) is a thermal depolymerization process that transforms wet organic waste into bio-crude oil that can be utilized as a fuel. On the other hand, fermentation is a biochemical process that converts organic waste into biogas, which can be harnessed to produce electricity or heat [18]. Using waste-to-energy techniques enables efficient waste management and facilitates the fulfillment of the energy requirements of the urban area through the generated energy. Selecting the most appropriate waste-to-energy (WtE) technique and scenarios for solid waste management, including the combination of different techniques, is a multifaceted undertaking. It requires consideration of several factors, including population requirements, environmental impact, cost, and health implications [19].

MCDM techniques offer a systematic methodology for assessing and prioritizing different solutions, considering multiple criteria [20]. These methodologies are especially advantageous when decision-makers deal with complex and contradictory objectives that cannot be readily resolved through a basic cost-benefit analysis. MCDM techniques have gained significant popularity in solid waste management (SWM) in recent times, owing to their suitability for addressing the inherent complexities of the problem.

MCDM techniques such as AHP, simple additive weighting (SAW), and grey relational analysis (GRA) are commonly used to evaluate and rank alternatives [21]. Regarding MCDM approaches, TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) are two commonly used techniques that can be applied to evaluate and rank scenarios in Lahore's solid waste management (SWM) system. Fuzzy logic can also be incorporated into TOPSIS and PROMETHEE to account for uncertainties in the decision-making process [22]. MCDM methods consist of a few steps, as shown in "Figure A" in supplementary material. The TOPSIS method involves identifying the ideal and anti-ideal solutions based on the selected criteria and calculating the distance between each scenario and these solutions [21]. The scenarios are then ranked based on their proximity to the ideal solution. The PROMETHEE methodology entails the development of a preference function that evaluates the net preference flow between every pair of scenarios, taking into account the chosen criteria [23]. This approach has been utilized in numerous research endeavors to assess and prioritize SWM options, considering various factors, including sustainability, equity, and efficiency. Solid waste management in developing nations, utilizing Istanbul, Turkey, as a case study, was examined [24]. Using three alternative MCDMs (TOPSIS, PROMETHEE I, and PROMETHEE II), the authors analyze eight potential solid waste disposal scenarios based on seven criteria established by experts in the area. The most suitable and feasible scenarios are determined, with recycling and landfill technologies emerging as prominent options for developing countries. The Grey-EDAS model evaluated waste treatment methods in Nigeria based on seven environmental, society, and cost criteria, with composting identified as the most effective [25]. The most relevant MCDM methodologies, such as AHP, multi-attribute utility theory (MAUT), Outranking procedures, and TOPSIS, suggest integrating various methods and tools or developing bespoke methodologies to optimize solid waste management [26]. The study was conducted on developing an optimized municipal solid waste management model using MCDM methods, specifically an improved version of Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Viekriterijumsko Kompromisno Rangiranje (VIKOR) compromise solution method [27]. The study compares and ranks 11 scenarios of MSW treatment methods based on environmental and economic criteria. The results suggest that integrating a sanitary landfill, RDF, composting, anaerobic digestion, and recycling is the optimized integrated waste management model.

In Lahore's SWM system, TOPSIS and PROMETHEE techniques can be used to evaluate and rank various scenarios based on waste reduction, recycling, energy recovery, and cost-effectiveness criteria. Integrating fuzzy logic into TOPSIS and PROMETHEE models effectively addresses uncertainties that may arise during the decision-making process.

The present study entails a thorough analysis to assess the potential of various waste-to-energy methodologies for effectively managing the significant amount of waste generated in Lahore. Data has been gathered from three distinct regions of the city, namely low-income, medium-income, and high-income areas, with the aim of assessing the potential for waste and identifying the most appropriate waste-to-energy technologies for the city's future. The identification of the most effective and sustainable solution for waste management in Lahore is achieved through the utilization of MCDMs, including TOPSIS, PROMETHEE, and fuzzy. The primary goal is to suggest a sustainable waste management resolution for Lahore that effectively addresses the existing waste management predicament while also fulfilling the city's energy requirements.

2. Methodology

2.1. Sampling and characteristics of the waste

The issue of solid waste management has emerged as a notable concern in Lahore, the metropolitan city of Pakistan. To effectively address this issue, a comprehensive study of the waste in the city has been conducted. The city has been divided into nine distinct towns based on income level by Lahore Waste Management Company (LWMC). The income levels of different towns in Lahore, Pakistan, have been categorized into two groups. The Circle-I region comprises four towns: Samanabad, Allama Iqbal, Gulberg, and Nishter. Samanabad and Nishter are classified as middle-income areas, while Allama Iqbal and Gulberg are categorized as high-income areas. Circle II comprises five towns: Ravi, Shalimar, Aziz Bhatti, Wahga, and DGBT. Ravi and DGBT are classified as middle-income areas, whereas the remaining three towns are designated as low-income regions. This information may prove valuable to policymakers, researchers, and individuals with an interest in the socio-economic development and planning of Lahore. A representative sample of solid waste is collected from each town, represented in Appendix A. The selection of collection areas for samples was based on factors such as population, geographic location, and land use in each town to ensure a representative sample of the waste composition of the city. The vehicles carrying waste were weighed prior to transportation to the study site in order to obtain precise data on the waste's area and quantity. In order to maintain uniformity in the sampling procedure, a sampling container with an open top and a capacity of 0.5 cubic meters was utilized. The containers were constructed from iron and featured a handle for convenient transportation. The waste was filled without any compression or gaps to ensure it accurately represented the waste generated in the city. The selection of a sampling volume of 0.5 m^3 was determined by its adherence to the ASTM standards for handling samples within the weight range of 91–136 kg. This measure ensured that the gathered samples were adequately sized to depict the waste composition of the city precisely. The sampling methodology utilized in this study was thorough and designed to achieve precise and inclusive data for waste characterization in Lahore.

The process of waste characterization holds significant importance in solid waste management. The process entails conducting a comprehensive analysis of solid waste samples through physical, chemical, and biological means to ascertain their composition, properties, and characteristics. The characterization of waste is a crucial factor in determining the appropriate waste management strategies, as the physical makeup of the waste plays a significant role in this decision-making process.

The physical composition of the solid waste samples obtained from the nine towns in Lahore is characterized. The components identified in Appendix B will be used as the basis for categorizing the waste. The waste is segregated into the respective categories, and the proportion of each constituent is determined. The data obtained from waste characterization is utilized to formulate solid waste management scenarios for Lahore. The analysis of the scenarios is conducted through the utilization of MCDM techniques such as TOPSIS, PROMETHEE II, AHP, and fuzzy. For several reasons, MCDM methods are crucial in Municipal Solid Waste (MSW) management. MSW management deals with costs, environmental impact, and public health. MCDM allows simultaneous consideration of these diverse criteria. MCDM provides an organized and objective approach. It quantifies criteria and minimizes subjective biases by assigning weights. Often, MSW decisions involve trade-offs, like cost versus environmental impact. MCDM systematically explores these trade-offs. Decision-makers can assess the consequences of different MSW strategies under varying conditions, aiding informed choices. MSW management involves multiple stakeholders. MCDM engages them, incorporates their preferences, and fosters inclusive decision-making. With the growing data availability in MSW, MCDM can leverage data analytics and modeling to enhance decision-making. MCDM techniques aid in determining the optimal solid waste management solution for Lahore, considering several evaluation criteria, including capex (capital expenditure), opex (operational expenditure), revenue generation, environmental impact, social impact, resource availability, and qualified personnel. The feedback from all the stakeholders was obtained to decide the evaluation criteria. These stakeholders included government agencies (Municipal solid waste corporation), environmental agencies, waste collection companies (Lahore waste management company), academicians, local businessmen, and the Local Communities.

According to the findings of the waste characterization analysis, the solid waste present in Lahore, Pakistan, comprises diverse components. A significant proportion of the waste comprises biodegradable materials, accounting for 54.32% of the total. According to the data, diapers and sanitary pads account for 15.78% of the total waste, whereas nylon comprises 9.41%. Additional constituents of the waste comprise non-combustible materials like stone and demolition waste (7.63%), textiles (6.02%), and combustibles that are not classified in other categories (3.09%). Glass and metals constitute a minor proportion of the overall waste, accounting for only 0.82% and 0.06%, respectively. Hazardous waste, such as batteries and medical waste, represents only 0.11% of the total waste. These results provide important information that can be used to identify the best waste management strategies for Lahore. The graph in "Figure C" in supplementary material shows the waste composition of Lahore city in terms of four categories: combustible, organic, non-combustible, and recycled. The organic waste category, including biodegradable waste, has the highest percentage of waste composition at 54.32%. The combustible waste category, including materials such as diapers, paper, nylon, Tetra Pak, and textiles, has a percentage of 36.32%. The non-combustible waste category, including glass, metal, and plastic, has a percentage of 7.63%, while the recycle waste category, including materials such as electronics/electrical, pet, and hazardous waste, has only 1.32%.

2.2. Questionnaire survey

The primary objective of the questionnaire survey was to systematically gather insights and perspectives from key stakeholders, encompassing university educators, staff members, and students. This initiative aimed to facilitate the development of optimal scenarios and evaluation criteria for Solid Waste Management (SWM). The overarching goal was to harness the diverse view points of academia and students alike, contributing to formulating comprehensive and efficacious strategies for managing solid waste. This survey was conducted by 16 university teachers (professors, associate professors, assistant professors, and lectures), 14 staff members, and more than 100 students.

In multi-criteria decision-making, the fundamental scale of comparison was utilized to assign relative importance to various criteria (refer to Appendix D). Stakeholders were specifically tasked with ranking different criteria, including but not limited to CAPEX, OPEX, revenue generation, environmental impact, social impact, resource availability, and the presence of qualified personnel. This ranking process involved a pairwise comparison, wherein each participating expert provided rankings for pairs of criteria.

For instance, a participant may assign a numerical value of 1 if they perceive social and environmental impacts equally significant. Conversely, another expert might assign a value of 5 if they strongly believe that CAPEX is more important than resource availability. This structured approach ensured a nuanced and comparative evaluation of diverse criteria, offering valuable insights into the relative priorities of the stakeholders involved.

2.3. MCDM techniques

The research employs three MCDM methodologies: the Analytical Hierarchy Process (AHP) with Fuzzy, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and PROMETHEE II. In conjunction with fuzzy logic, the Analytic Hierarchy Process (AHP) will be employed to assign weights to the criteria and scenarios based on their respective significance levels. Incorporating fuzzy logic will facilitate the management of imprecise and uncertain data by decision-makers. The TOPSIS and PROMETHEE II methods are used to evaluate the scenarios. In TOPSIS, the best choice is the one that is the closest to the optimal solution and the farthest from the anti-ideal one. Table 1 depicts the first step of the TOPSIS technique, which is to generate a decision matrix. The elements of the decision matrix are then used in Equation (1) to derive a normalized decision matrix [28].

$$a_{ij} = \frac{r_{ij}}{\sqrt{\sum_{k=1}^{m} r_{kj}^{2}}} \quad (1)$$

Where; $i = 1, 2, 3, \ldots.m.$

$$j = 1, 2, 3, \ldots.. n$$

r_{ij} depicts the criteria of the decision matrix.

In addition, the values in the normalized decision matrix are multiplied by the weight value for each criterion, using Equation (2), to get a weighted normalized decision matrix.

$$n_{ij} = a_{ij} \,.\, w_j \quad (2)$$

Where w represented a set of weights associated with the criteria of the decision matrix.

When making a choice, it is common practice to choose the option most similar to the best possible outcome. In this condition, a vector of "positive ideal solution (PIS)" maximizes revenues, and a vector of "negative ideal solution (NIS)" maximizes expenses. The chosen location should be near the PIS and distant from the NIS, as predicted by TOPSIS.

The Euclidean Distance Approach is then used to calculate the offsets of each decision point from the positive ideal and negative ideal solutions once the weighted standard decision matrix has been obtained. Then, using the positive ideal separation measures (S_{i^+}) and negative ideal separation measures (S_{i^-}), we can determine how close various options are to the optimal solution (C_{i^*}). The relative closeness of each alternative to the ideal solution is obtained [29].

$$C_{i^*} = \frac{S_{i^-}}{(S_{i^+} + S_{i^-})} \quad (3)$$

In Equation (3), if $C_{i^*} = 1$, the alternative is deemed the action, and if $C_{i^*} = 0$, the alternative is deemed the non-optimal one. Finally, the values C_{i^*} are used to rank the possibilities, with the greatest value signifying the best choice.

The PROMETHEE II methodology will be employed to validate the outcomes of the AHP approach with fuzzy and TOPSIS techniques and to determine the most resilient solution. PROMETHEE II will simulate the decision-making process by considering the decision-makers' preferences and aspirations. Combining these three MCDM techniques will provide a comprehensive and robust framework for evaluating the municipal solid waste management options in Lahore, Pakistan.

2.4. Scenarios

To manage the solid waste in Lahore, the experts have generated ten suitable scenarios based on the physical composition of the collected waste. These scenarios are formulated by considering the specific percentage compositions of various ingredients as key determinants. The selection and combination of these ingredients play a pivotal role in shaping the outcomes and variables within each scenario. For example, scenario 1 considers 100% Landfill, and scenario 5 considers 54% composting, 37% gasification, and only 9% landfill. The detailed composition of all the scenarios is provided in Table 2.

The segregation process of municipal solid waste divides waste into four main sections. The ten scenarios are based on these four sections of solid waste: organic fractions, combustibles, non-combustibles, and recyclables. The categorization of municipal solid waste and accompanying scenario specifics are shown in Fig. 1.

2.5. Evaluation criteria

The fundamental scale of comparison, a critical tool in MCDM, assigns relative importance to various criteria. This scale is instrumental in simplifying the process of conducting pairwise comparisons among different criteria. It spans from 1 to 9, and each number on the scale carries specific significance. When two criteria or alternatives receive a weight of 1, they hold equal importance in decision-making. A rating of 3 reflects a slight preference for one criterion or alternative over another. A score of 5 indicates a moderate preference. The criterion or alternative with the higher score is moderately more important. With a value of 9, there is a profound preference for one criterion or alternative. The one with the higher score is considerably more important. For values between these,

Table 1
Positive and negative Ideal solution values.

Criteria	(Positive Ideal Solution) PIS	(Negative Ideal Solution) NIS
CAPEX	0.0311	0.0039
OPEX	0.0146	0.0027
Revenue Generation	0.1099	0.0110
Environmental Impact	0.1790	0.0422
Social Impact	0.1361	0.0257
Resource Availability	0.0622	0.0081
Qualified Personnel	0.0612	0.0100

Table 2
Solid waste management scenarios.

Sr. No.	Scenarios
1	Landfill (100%)
2	RDF (37%) + Landfill (63%)
3	Composting (54%) + RDF (37%) + Landfill (9%)
4	Composting (54%) + Incineration (37%) + Landfill (9%)
5	Composting (54%) + Gasification (37%) + Landfill (9%)
6	Composting (54%) + HTL (37%) + Landfill (9%)
7	AD (54%) + RDF (37%) + Landfill (9%)
8	AD (54%) + Incineration (37%) + Landfill (9%)
9	AD (54%) + Gasification (37%) + Landfill (9%)
10	Fermentation (54%) + RDF (37%) + Landfill (9%)

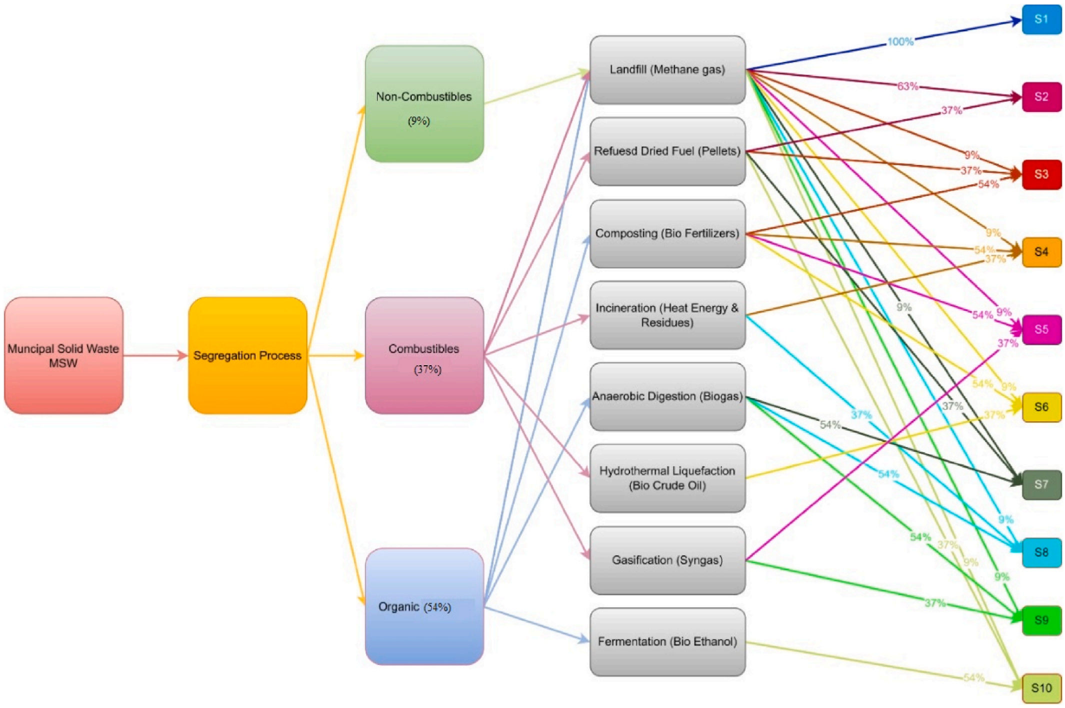

Fig. 1. Flowchart of scenario details.

such as 2, 4, 6, and 8, they can be employed to express intermediate degrees of preference. This 1-9 scale allows decision-makers to quantify their subjective judgments regarding the relative importance of criteria or alternatives. This quantification streamlines the process of conducting pairwise comparisons and calculating weighted scores for more informed decision-making. The decision-makers involved various stakeholders, including government agencies (such as the Municipal Solid Waste Corporation), environmental agencies, waste collection companies (including the Lahore Waste Management Company), academicians, local businessmen, and local communities. When two criteria or alternatives receive a weight of 1, they hold equal importance in decision-making.

To ascertain the most appropriate management scenario for MSW, we shall assess each scenario based on the following criteria: Capital expenditure (Capex) refers to the total investment necessary for establishing and operating the municipal solid waste (MSW) management system. Operating Expenditure (Opex) refers to the overall expenses incurred in managing the municipal solid waste (MSW) system, encompassing labor, equipment, and maintenance costs. Potential for Revenue Generation: The MSW management system has the potential to generate revenue through the sale of recyclable materials or energy. Environmental Impact: The assessment of the impact of the municipal solid waste (MSW) management system on the environment, encompassing the potential effects on air, water, and soil quality, as well as the emission of greenhouse gases and the contribution to climate change. Social Impact: The effect of the MSW management system on the community, encompassing aspects such as public health, safety, and overall quality of life. Resource availability refers to the accessibility of essential resources, including land, labor, and energy, necessary to manage municipal solid waste effectively. One of the key factors for the effective operation of the MSW management system is the availability of qualified personnel, including engineers, technicians, and managers. Fig. 2 summarizes the MCDM methodology utilized to address the solid waste management (SWM) issue in Lahore, Pakistan.

3. Result and discussion

This study used an MCDM approach to evaluate and select the most appropriate solid waste management strategy for Lahore, Pakistan. All the coding was done at "Jupyter Notebook" (An integrated development environment of Python). The code used for the analysis can be accessed at (https://github.com/Amjad-IFTMI/WasteManagementLHR/tree/a22809ce99e7551c6488234501c30a0c17e5c312). The evaluation is based on seven criteria. The fundamental scale of comparison is used to assign relative importance to criteria in MCDM [30]. It is a common tool used to facilitate the process of pairwise comparisons between different criteria. The scale ranges from 1 to 9, with each number having a specific meaning. The scale Thomas Saaty developed is shown in Appendix D [31]. We investigate the potential of triangular fuzzy numbers (TFNs) for facilitating the transformation of independent variables into fuzzy sets. The last step involves turning the fuzzy sets into discrete numbers. Since triangular fuzzy membership functions are effective and easy to implement, they are preferred. Whether or not a membership function can reliably determine the kind of input is a major factor in determining whether or not it should be used. Mathematical operations are used to assess the relevance of the considered qualities or the relative pair-wise comparison, and this involves using a scale specified between 1 and 9. The fundamental scale conversion into a triangular fuzzy number is presented in Appendix E. Building a pair-wise comparison matrix is one of the most important steps in using Fuzzy AHP to determine the relative importance of criteria [32]. The replies from the experts are used to populate a weighting matrix, where the values represent the importance of different criteria. The decision-making procedure is represented in a more precise manner by using a fuzzy AHP approach. The comparison matrix, in which seven criteria were compared head-to-head, is shown in Table 3. Table 3 shows pairwise comparisons among different criteria. For example, Environmental Impact is 5 times more important than revenue generation. Similarly, qualified personnel have 3 times more importance than social impact, and social impact is 0.333 times less important than qualified personnel.

The arithmetic means of all the weights acquired is used to establish the final weightage of each criterion, as shown in Table 4. The consideration of environmental implications is given the greatest weightage value (0.338), making it the most important factor in solid waste management. The findings reveal that operating expenditure (OPEX) cost is viewed as the least relevant criterion for dealing with waste.

These findings point to Environmental Impact as the most crucial factor in determining the best action for municipal solid waste management in Lahore, Pakistan. This lines up with the increasing awareness of the environmental impacts of our current waste management methods and the resulting emphasis on long-term, low-impact alternatives. The findings also indicate that revenue generation is a critical factor, showing the monetary weight of waste management choices. These values will be utilized in the next stage of the MCDM process to rank the various waste management strategies and ultimately choose the most suitable one for Lahore, Pakistan. The decision matrix is the result of comparing each possible outcome to a set of predetermined criteria and giving weights to those criteria. To determine how much weight each criterion should be given, we turned to a fuzzy approach, a method for making decisions that consider many criteria and their relative relevance. The FAHP approach uses linguistic variables to handle uncertainties and vagueness in human judgment and decision-making [33]. On the other hand, the scenario weights were obtained using the analytic hierarchy process (AHP) approach, a decision-making tool that allows for the pairwise comparison of criteria and scenarios to determine their relative importance. Applying AHP, a tried-and-true method for making MCDMs, has proven useful in many different areas, from engineering and economics to environmental management. The performance of the scenarios against each criterion is

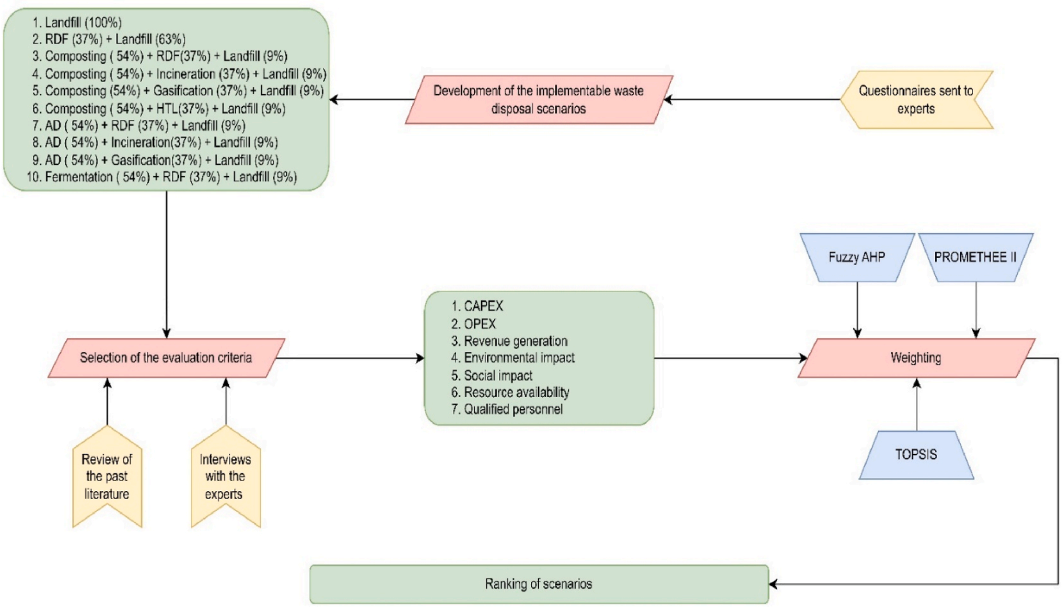

Fig. 2. Flowchart of the methodological analysis.

Table 3
Fundamental scale pair wise comparison.

	CAPEX	OPEX	Revenue Generation	Environmental Impact	Social Impact	Resource Availability	Qualified Personnel
CAPEX	1.0000	7.0000	0.3333	0.2000	0.2000	0.2000	0.3333
OPEX	0.1428	1.0000	0.2000	0.2000	0.2000	0.3333	0.33333
Revenue Generation	3.0000	5.0000	1.0000	0.2000	0.3333	5.0000	3.0000
Environmental Impact	5.0000	5.0000	5.0000	1.0000	1.0000	5.0000	5.0000
Social Impact	5.0000	5.0000	3.0000	1.0000	1.0000	5.0000	0.3333
Resource Availability	5.0000	3.0000	0.2000	0.2000	0.2000	1.0000	5.0000
Qualified Personnel	3.0000	3.0000	0.3333	0.2000	3.000	0.2000	1.0000

Table 4
Criteria with Fuzzy weights.

	Fuzzy Weights			Mi	Weights
CAPEX	0.03664	0.05273	0.0808	0.0567	5.41%
OPEX	0.02108	0.03024	0.0464	0.0326	3.11%
Revenue Generation	0.10453	0.16042	0.2442	0.1697	16.19%
Environmental Impact	0.24460	0.34396	0.4768	0.3551	33.88%
Social Impact	0.14908	0.21717	0.3155	0.2272	21.68%
Resource Availability	0.06917	0.10128	0.1488	0.1064	10.16%
Qualified Personnel	0.0601	0.0941	0.1464	0.1002	9.56%

shown below in Table 5. Table 5 shows the comparison of costs for different scenarios. For example, the value of CAPEX for S1 is 0.21, and for S2 is 0.22, which shows that CAPEX for S2 is slightly higher than for S1. Now, for CAPEX, OPEX, and revenue generation, these are original costs obtained through different suppliers of these technologies in this region. The values are taken in USD to avoid currency depreciation. At the same time, the values for environmental impact, social impact, resource availability, and qualified personnel are based on experts' opinions and relevant literature. Then, their pairwise comparison ratios are used in Table 5.

Table 6 displays the results of applying the appropriate formulas of the TOPSIS technique to rank the possible scenarios.

The performance of several scenarios for waste management is compared in the table, which considers a wide range of factors. When considering municipal solid waste management in Lahore, Pakistan, the results show that the S9 comes closest to the ideal solution. According to the results, S1 is the poorest option since it is the least similar to the best one. The TOPSIS technique, in general, is a helpful tool for assessing and rating various waste management scenarios according to a number of criteria.

Compared to other scenarios, scenario (S9) ranks first in TOPSIS analysis due to its high closeness to the ideal solution (C_{i^*}). The assessed scenario is separated from both the positive and negative ideal solutions by a distance (C_{i^*}), which is computed using the Euclidean distance formula. In this case, the highest (C_{i^*}) is associated with S9, which has the smallest distance to (S_{i^+}) and the largest distance to (S_{i^-}). When all criteria and weights are considered, it becomes clear that S9 outperforms the other scenarios under consideration.

S9 outperformed other scenarios due to a combination of factors, including the fact that the scenario involves the use of Anaerobic Digestion (AD) and Gasification technologies, which have been shown to be effective in converting organic waste into energy while

Table 5
Performance of the scenarios against each criterion (Decision Matrix).

	Criteria Weights	0.05	0.03	0.16	0.34	0.22	0.10	0.10
	Scenarios	CAPEX	OPEX	Revenue Generation	Environmental Impact	Social Impact	Resource Availability	Qualified Personnel
S1	100% Landfill	0.21	0.13	0.03	0.04	0.04	0.03	0.24
S2	RDF (37%) + Landfill (63%)	0.22	0.17	0.03	0.05	0.04	0.04	0.16
S3	Composting 54% + RDF 37 % + Landfill 9%	0.13	0.08	0.06	0.09	0.09	0.23	0.14
S4	Composting 54% + Incineration 37 % + Landfill 9%	0.12	0.05	0.10	0.05	0.05	0.17	0.10
S5	Composting 54% + Gasification 37% + Landfill 9%	0.04	0.05	0.06	0.11	0.12	0.09	0.07
S6	Composting 54% + HTL 37% + Landfill 9%	0.05	0.03	0.15	0.19	0.11	0.06	0.04
S7	AD 54 % +RDF 37% + Landfill 9%	0.07	0.17	0.09	0.14	0.11	0.18	0.09
S8	AD 54 % + Incineration 37% + Landfill 9%	0.08	0.10	0.15	0.08	0.06	0.08	0.07
S9	AD 54% + Gasification 37% + Landfill 9%	0.03	0.08	0.09	0.19	0.23	0.05	0.04
S10	Fermentation 54% + RDF 37% + Landfill 9%	0.05	0.15	0.26	0.05	0.15	0.06	0.06

Table 6
TOPSIS final ranking and computation.

	Scenarios	S_{i^+} (Positive Ideal Solution)	S_{i^-} (Negative Ideal solution)	C_{i^*} (Closeness to Ideal solution)	Rank
S1	100% Landfill	0.2088	0.0580	0.2176	9
S2	RDF (37%) + Landfill (63%)	0.2017	0.0442	0.1797	10
S3	Composting 54% + RDF 37 % + Landfill 9%	0.1526	0.0829	0.3520	6
S4	Composting 54% + Incineration 37 % + Landfill 9%	0.1836	0.0545	0.2290	8
S5	Composting 54% + Gasification 37% + Landfill 9%	0.1433	0.0834	0.3679	5
S6	Composting 54% + HTL 37% +Landfill 9%	0.1131	0.1489	0.5682	2
S7	AD 54 % + RDF 37% + Landfill 9%	0.1183	0.1134	0.4894	3
S8	AD 54 % + Incineration 37% + Landfill 9%	0.1663	0.0626	0.2735	7
S9	AD 54% + Gasification 37% + Landfill 9%	0.1053	0.1778	0.6279	1
S10	Fermentation 54% + RDF 37% + Landfill 9%	0.1555	0.1201	0.4357	4

reducing greenhouse gas emissions. Furthermore, in this scenario, landfilling is used as little as possible, which helps lessen the negative environmental effects that landfills often cause. Additionally, the scenario was rated fairly highly on criteria like social impact.

PROMETHEE is an example of an outranking approach that uses each alternative's positive and negative preference flows to determine its final ranking. The positive outranking flow (φ^+), describes how an alternative is preferred over all other alternatives, and the negative outranking flow (φ^-), expresses how an alternative is preferred over all other alternatives. Both are computed using the weights assigned to the preferences. The net outranking flow (φ), the difference between the positive and negative outranking flows, is displayed in Table 7 and is the basis upon which PROMETHEE II constructs its final ranking.

With a net outranking flow φ of 0.30, the PROMETHEE II results show that Scenario 9 is the optimal plan for the waste management system. According to the φ value, this scenario outperforms the others iregardingoverall performance Scenario S6 ($\varphi = 0.182$) is the best alternative. In terms of net outranking flow (φ), these scenarios rank highest, suggesting they are the best choices These scenarios are prioritized because they have greater weight in the decision criterion matrix than those trioritized the most. According to the AHP analysis, the categories of environmental effect and social impact have the highest weight. The PROMETHEE II results prank higheron the scenarios that performed well in these criteria. With a φ of -0.202, S1 (100% landfill) is the worst-performing scenario. Since this scenario has a negative φ value, it is less likely than any other possible outcome.

In comparing TOPSIS and PROMETHEE II methods for Municipal Solid Waste Management in Lahore, Pakistan, Scenario 9 (AD 54% + Gasification 37% + Landfill 9%) was ranked 1 in both methods. According to the TOPSIS method, Scenario 9 had the highest (C_{i^*}) value of 0.627955492, which indicates the closest proximity to the ideal solution. This scenario had the highest rank in terms of closeness to the ideal solution. Similarly, in the PROMETHEE II method, Scenario 9 had the highest net flow value of 0.299040081, indicating the highest preference score. It was compared with all other scenarios in pairs and had the highest net flow value for most comparisons. Thus, Scenario 9 had the highest ranking in PROMETHEE II. This can be shown in the figure below. The net outranking flow for PROMETHEE-II and TOPSIS Score (Ci+) are plotted on the graph to compare PROMETHEE and TOPSIS results. The values on the Y-axis show the same. The graph indicates that both techniques provide consistent results for the top-ranked alternatives. S9 has the highest net outranking flow and Ci+, followed by scenarios 6 and 7.

In the context of the TOPSIS method, Scenario 9 emerged as the frontrunner, displaying the highest proximity to the ideal solution, indicative of its remarkable alignment with the best possible outcome. Likewise, within the PROMETHEE II method, Scenario 9 boasted the highest net flow value, underscoring its unmatched preference score when evaluated against competing scenarios. The outcomes derived from the comparative analysis of the TOPSIS and PROMETHEE II methods Fig. 3, as applied to Municipal Solid Waste Management in Lahore, Pakistan, yield substantial insights crucial for informed decision-making in waste management strategies. Comparable research endeavors within the literature employ MCDMs to advocate for strategies that facilitate the conversion of waste into energy. PROMETHEE was utilized to rank three municipal solid waste management alternatives within a metropolitan area in

Table 7
PROMETHEE II final ranking and computation.

Scenarios	Leaving Flow (φ^+)	Entering Flow (φ^-)	Net outranking flow (φ)	Rank
S1	0.12	0.32	−0.20	10
S2	0.09	0.29	−0.19	9
S3	0.19	0.16	0.03	4
S4	0.10	0.25	−0.15	8
S5	0.15	0.17	−0.03	6
S6	0.31	0.12	0.18	2
S7	0.26	0.10	0.16	3
S8	0.10	0.21	−0.12	7
S9	0.42	0.12	0.30	1
S10	0.22	0.21	0.01	5

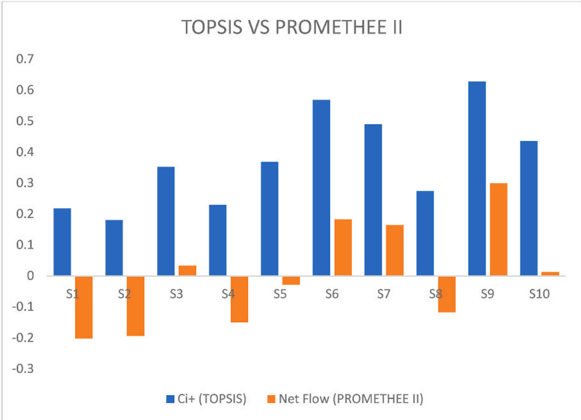

Fig. 3. Comparison between the results of TOPSIS and PROMETHEE II.

Brazil [34]. Life cycle assessment and multi-criteria decision analysis were applied to choose an optimal strategy for managing domestic food waste in Rio de Janeiro [35]. Healthcare waste disposal techniques were evaluated in Shanghai, one of China's largest cities, employing a VIKOR-based fuzzy MCDM approach [36].

Scenario 9, characterized by a sequence of anaerobic digestion (AD), gasification, and landfilling, consistently clinched the top-ranking position across both methods. Moreover, it's worth noting that both methods yield identical results when ranking the 2nd and 3rd scenarios; S6 secures the second position, while S7 claims the third. However, there is a disparity in ranking the lowest-performing scenarios between the two techniques. TOPSIS assigns the lowest rank to S2, whereas PROMETHEE II designates S10 as the least favorable. For an in-depth comparison of results generated by both methods, please refer to Tables 6 and 7 A detailed comparison of results for both techniques is provided in Tables 6 and 7

These findings hold pivotal significance for decision-makers, as Scenario 9 presents a highly effective waste management strategy that significantly curtails the volume of waste destined for landfills. This reduction is of paramount importance, as it extends the operational lifespan of landfills while concurrently mitigating their adverse environmental impact. The incorporation of AD and gasification processes in Scenario 9 embodies a sustainable approach by yielding biogas and syngas. This dual benefit reduces waste and harnesses renewable energy resources, thus contributing substantially to environmental sustainability. Notably, AD and gasification processes are recognized for their capacity to curtail greenhouse gas emissions and ameliorate air quality, aligning seamlessly with global initiatives to combat climate change and enhance air purity. The specific insights gleaned from the performance of Scenario 9 possess direct relevance to the prevailing waste management challenges in Lahore. Decision-makers in the city can judiciously contemplate adopting analogous waste-to-energy approaches, tailor-made to suit local circumstances and constraints.

4. Conclusion

The research conducted on municipal solid waste management in Lahore, Pakistan, using MCDM methods has yielded valuable insights. The primary aim of this study was to assess various waste management scenarios from multiple perspectives, including environmental, social, and economic considerations, with the goal of identifying the most effective option. Four MCDM methods—fuzzy, AHP, TOPSIS, and PROMETHEE II—were employed to rank 10 distinct waste management scenarios based on seven criteria. The analysis revealed that the top-performing waste management scenarios were Scenario 9 (AD 54% + Gasification 37% + Landfill 9%), Scenario 6 (Composting 54% + HTL 37% + Landfill 9%), and Scenario 7 (AD 54% + RDF 37% + Landfill 9%). Among these, Scenario 9 emerged as the most successful choice due to its lower environmental impact and higher social acceptability. Furthermore, it was deemed the most technically and economically viable option compared to Scenarios 6 and 7. Scenario 6 ranked second behind Scenario 9, primarily due to its greater environmental impact and lower societal acceptability. However, it remained technically and economically feasible, making it preferable to Scenario 7, which ranked third due to its larger environmental effect and lower societal acceptability.

Despite these promising findings, there are certain limitations to this research. Firstly, the study's results are context-specific to Lahore, Pakistan, and may not directly apply to other regions with distinct waste management challenges and social contexts. Additionally, the analysis heavily relies on available data and assumptions, which may introduce uncertainties in the decision-making process. Furthermore, the assessment is based on current conditions and may not account for future changes in waste generation or technological advancements in waste management.

Nonetheless, this research underscores the significance of identifying an appropriate waste management scenario that considers environmental, social, and economic aspects, particularly in a city like Lahore, where inadequate waste management practices have led to environmental and health problems. The utilization of MCDM techniques has proven effective in this decision-making process, with the four methods used in this study complementing each other and providing robust results. These findings have practical implications for policymakers and stakeholders in crafting a comprehensive waste management strategy for Lahore, aiming to mitigate waste-related issues, create job opportunities, reduce open dumping, minimize environmental impacts, and stimulate economic growth. The Lahore Waste Management Company (LWMC) is poised to implement the insights gained from this research into its waste management practices, which have the potential to improve the waste management situation in the city significantly. However, ongoing monitoring and adaptation of the chosen scenario will be necessary to address evolving challenges and ensure long-term success.

CRediT authorship contribution statement

M.A. Mujtaba: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Adeel Munir:** Writing – review & editing, Software, Investigation, Formal analysis. **Shahid Imran:** Writing – review & editing, Project administration, Data curation. **Muhammad Kamran Nasir:** Writing – review & editing, Data curation. **M. Ghulam Muhayyuddin:** Writing – review & editing, Methodology, Data curation. **Abdullah Javed:** Writing – review & editing, Data curation. **Amjad Mehmood:** Writing – review & editing, Validation, Software, Formal analysis. **Mohamed A. Habila:** Writing – review & editing, Funding acquisition. **H. Fayaz:** Writing – review & editing, Funding acquisition. **Atika Qazi:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

AHP	Analytical herichery process
AD	Anaerobic Digestion
CAPEX	Capital expenditure
GRA	Grey relational analysis
HTL	Hydrothermal liquefaction
LWMC	Lahore waste management company
MSWM	Municipal solid waste management
MCDM	Multi-criteria decision making
MAUT	Multi-attribute utility theory
NIS	Negative ideal solution
OPEX	Operating Expenditure
PROMETHEE II	Preference Ranking Organization Method for Enrichment Evaluations
PIS	Positive ideal solution
RDF	Refuse-derived fuel
SDG's	Sustainable development goal
SWM	Solid waste management
SAW	Simple additive weighting
TFN's	Triangular fuzzy numbers
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
VIKOR	Viekriterijumsko Kompromisno Rangiranje
WtE	Waste to energy

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e25788.

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