



A Comprehensive Framework for Selecting Waste-to-Energy Technologies in Iran: A Multi-Criteria Decision-Making Approach

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Abstract

Sustainable energy supply is a critical challenge in developing countries, particularly Iran, where fossil fuels dominate energy production. The environmental consequences of fossil fuel reliance, including greenhouse gas emissions and climate change, underscore the need for alternative energy sources. Municipal solid waste (MSW) represents a significant biomass resource with potential for energy generation, offering a dual solution to waste management and energy needs. This study aims to evaluate six waste-to-energy (WtE) technologies—incineration (INC), gasification (GAS), plasma (PL), landfill gas (LFG), pyrolysis (PYR), and anaerobic digestion (AD)—using a multi-criteria decision-making (MCDM) approach. Four sustainability dimensions—economic, environmental, social, and technical—were assessed through twelve sub-criteria, employing the Best-Worst Method (BWM) for weighting and the Measurement Alternatives and Ranking according to Compromise Solution (MARCOS) method for ranking the technologies. The results suggest that landfill gas is the most suitable WtE technology for Iran, providing optimal waste volume reduction and significant potential for renewable energy generation. This study provides a strategic framework aimed at improving waste management and fostering sustainable energy production in Iran, thereby facilitating the shift from a linear economy to a circular one.

Keywords:

Biomass; Bioenergy; Waste Management, Sustainability; BWM; MARCOS.

Introduction

Access to affordable and dependable energy is essential for promoting sustainable development and driving economic progress within any society [1]. The expansion of renewable energy sources is crucial for achieving the goals outlined in the United Nations' 2030 Agenda for Sustainable Development and for fulfilling the commitments established by the Paris Agreement on Climate Change [2]. Fossil fuels represent the predominant source of energy production in Iran. However, their continued use as the primary energy source not only depletes finite reserves but also exacerbates environmental challenges such as climate change, acid rain, global warming, air pollution and other related concerns [3]. In such a situation, the prospect of energy production in the next few decades will face serious challenges. This has encouraged

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countries worldwide to use clean and renewable energy to generate energy.

Biomass, which can be converted into bioenergy, is considered a suitable alternative to fossil fuels. This energy source, besides being renewable, is also environmentally friendly [4]. Biomass resources include MSW, agricultural and forestry residues, animal manure, food industry waste, municipal wastewater, and energy crops [5]. Since biomass resources include a wide range of available materials they can meet the needs of different sectors of human society [6]. This is one of the distinguishing features of biomass energy from other renewable energies. Among these sources, MSW is recognized as one of the most abundant, affordable, and accessible biomass energy sources. Improper management of these wastes can lead to numerous problems.

MSW refers to food waste and other solid materials, such as plastics and textiles, produced in urban communities, such as residential and commercial centers [7]. Waste contains energy stored within its chemical bonds, which, when broken, release significant amounts of energy [8]. MSW represents a valuable, renewable, and cost-effective resource, capable of producing usable solid, liquid, and gaseous fuels to address energy demands [9]. In developing countries like Iran, industrial growth, rapid urbanization, economic progress, unsustainable consumption patterns, and rising living standards have contributed to the increasing generation of MSW [10].

Mismanagement of MSW, through improper treatment and disposal, represents a major global challenge to sustainable development [11]. This issue leads to harmful environmental damage and social and economic concerns, such as nitrogen pollution, groundwater pollution caused by leachate, greenhouse gas emissions, and threats to public health [12]. Consequently, an effective waste management system that conserves valuable resources, reduces society's dependence on waste disposal, and helps recover resources is the need of the day.

Waste-to-Energy represents an effective strategy for generating clean energy while simultaneously managing waste [13]. Through the conversion of waste into energy, WtE technologies offer an integrated solution to the dual challenges of energy generation and waste disposal, while simultaneously mitigating associated environmental impacts [8]. These technologies effectively harness MSW as a dependable and sustainable source of clean energy [14]. Beyond reducing waste, deploying WtE systems facilitates resource recovery and promotes recycling. This approach contrasts with the conventional linear economy, which follows a "take, make, dispose" model. Instead, WtE technologies drive progress toward a circular economy, an essential paradigm for achieving sustainable development.

Implementing WtE technologies is critical in facilitating the shift from a linear to a circular economy [15]. Moreover, WtE technologies provide a comprehensive solution to energy consumption, waste management, and environmental challenges. Therefore, this study aims to evaluate WtE technologies in alignment with Iran's conditions, with a focus on progressing toward a circular economy. In the study of the sustainability of the waste management system, four sustainability axes have been addressed very little, and the focus has been more on the economic and environmental criteria. In some cases, only three sustainability criteria are considered in the model's design. This study evaluates WtE technologies—including plasma, gasification, pyrolysis, incineration, landfill gas, and anaerobic digestion—across four sustainability axes: economic, social, environmental, and technical, using twelve related sub-criteria with the aim of energy extraction. This study can pave the way for the formulation of supportive policies aimed at promoting the use of renewable resources and supporting Iran's shift from a linear economy to a more sustainable circular economy.

Literature Review

In response to growing concerns over environmental pollution and the energy crisis, biomass energy has gained attention as a sustainable source for electricity generation, heating, and

transport fuels. Subsection (2-1) examines recent studies focusing on biomass energy. Due to rapid population growth and increased waste generation, MSW has become a valuable source of biomass energy. WtE offer a groundbreaking solution for waste management by efficiently converting waste into usable energy. In this regard, several recent studies are discussed in Subsection (2-2).

Biomass Energy

In response to population growth and the depletion of fossil resources, Suvitha et al. (2024) underscore the significance of biomass energy production. Their study introduces a framework for evaluating various biomass resources using advanced methodologies. The findings reveal that agricultural residues offer the highest potential for bioenergy production, followed by MSW [16].

Yadav et al. (2024) conducted a study on the challenges hindering the implementation of bio WtE solutions in developing countries, identifying sixteen key challenges across economic, technical, social, and institutional dimensions. Using the Analytical Hierarchy Process (AHP), they ranked logistical difficulties and high initial investments as the most significant obstacles, underscoring the need for enhanced funding mechanisms and trained technicians to facilitate BTE adoption [17]. In a related study, Shahzad et al. (2023) applied the Pythagorean Fuzzy-AHP to assess the challenges in developing biomass energy in Pakistan. Their results point to political and institutional barriers as the most critical, with political instability identified as a secondary yet highly influential factor. The study recommends policy reforms, financial structures, and heightened environmental awareness, alongside stronger international cooperation, to mitigate these barriers [18].

Alves et al. (2024) investigated the potential of forest residues as a source of biomass energy in Portugal, where annual wildfire risks pose significant challenges. Their research suggests that the valorization of forest residues can reduce wildfire risks while enhancing the country's energy independence [19]. Similarly, AlNouss et al. (2024) investigated the conversion of five biomass waste types— food waste, MSW, camel dung, date seeds, and sewage sludge—into value-added products in Qatar. Their study reveals that GAS is the most economically viable option, while PYR yields the highest energy output. Additionally, hydrothermal liquefaction demonstrates superior environmental performance [20].

Municipal Solid Waste

MSW is a significant biomass energy source, and its management has emerged as a critical environmental challenge in developing countries, driven by population growth and increasing waste production. In recent years, MCDM methods have gained prominence in MSW management, as these tools align well with the complex nature of the issue [21]. Waste management is a complex process encompassing environmental, economic, and social dimensions. MCDM techniques provide a structured framework to improve the decision-making process. Table 1 provides an overview of recent studies employing MCDM techniques in the field of MSW management.

Table 1. Summary of previous studies utilizing MCDM approaches in MSW management

Ref.	MCDM Method	Evaluation criteria					Treatment technology	Aim	Main findings
		Eco	Env	Soc	Tech	Oth			
[22]	AHP	✓	✓	-	✓	-	RDF, INC, AD, LFG	- Assess the state of waste management and	-LFG was the preferred WtE technology for

								energy sectors to identify the most suitable WtE.	Moscow, followed by AD and INC, while RDF was the least preferred
[23]	F-MULTIMOORA, F-AHP,	✓	✓	✓	✓	-	AD,LFG, INC,PYR ,GAS	-select the most appropriate WtE technology for Cape Town	- In Cape Town, the most sustainable WtE option for investment is AD, followed by GAS, PYR, and INC.
[24]	AHP, F-TOPSIS	✓	✓	✓	✓	-	AD, GAS, PYR, PL	-Evaluate and select optimal WtE for implementation in Ghana.	- Technical criteria were prioritized. -AD was the top technology, followed by GAS and PYR.
[25]	SF-ELECTRE III, SF-PROMETHEE	✓	✓	✓	✓	✓	INC,GAS ,PYR,PL	-Develop a MCDM technique using the SF-ELECTRE III method for selecting the most suitable WtE from MSW in the Azerbaijan region of Iran.	-Developed the SF-ELECTRE III method. - PL has been determined to be the most sustainable WtE technology for Iran's Azerbaijan region.
[26]	FFS, CODAS, CRITIC	✓	✓	✓	-	✓	Combustion,AD, GAS,PYR, LFG	-Evaluate the energy generation potential of different types of MSW, including plastic, electronic, organic, wood, and hazardous waste.	-MSW has significant potential as a renewable energy source - Organic waste is the most viable option for energy generation due to its economic efficiency and substantial electricity generation capacity.
[27]	F-logic, AHP, PROMETHEE II,TOPSIS	✓	✓	✓	-	✓	Use ten scenarios	-Evaluate and identify sustainable MSW management scenarios for Lahore, Pakistan	- Scenario 9. (54% AD + 37% GAS + 9% landfill) was identified as the most effective option
The current study	BWM, MARCOS	✓	✓	✓	✓	-	AD,LFG, INC,PYR ,PL,GAS	-Conducting a comprehensive evaluation and ranking of the most sustainable WtE conversion technologies for managing MSW in Iran.	-LFG technology was identified as the optimal WtE solution for Iran, owing to its dual benefits of renewable energy generation and cost-effectiveness, making it a practical choice for waste management.

Note: Eco: Economic, Env: Environmental, Soc: Social, Tech: Technical, RDF: Refuse derived fuel, FFS: Fermatean Fuzzy System, CODAS: Combinative DIXET Method for Multi-prioritization, CRITIC: Criteria Importance Through Intercriteria Correlation, SF-ELECTRE: Spherical Fuzzy- Elimination Et Choice Translating Reality, PROMETHEE: Preference Ranking Organization Method for Enrichment Evaluation, TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution, MULTIMOORA: Multi-Objective Optimization on the basis of Ratio Analysis plus full multiplicative form.

Problem Description and the Proposed Methodology

This research introduces a framework for evaluating and selecting the most sustainable technologies for converting MSW into energy in Iran. The admirable goal is to enhance waste management practices and optimize the use of waste as a renewable energy source. To achieve this goal, an MCDM model is employed to assess various technologies.

This framework includes four key sustainability dimensions, which are divided into twelve carefully selected sub-criteria, details of which are provided in Subsection (4-1). In Subsection (4-2), six alternatives are introduced for energy recovery from MSW. In Subsection (4-3), the integrated MCDM method, which combines the BWM and MARCOS, is presented. Criteria weighting is performed using the BWM, and the MARCOS method is applied for the final evaluation and ranking of technologies. To obtain a comprehensive overview of the research process, Figure (2) draws a schematic representation of the proposed methodology. Details regarding the different steps of this framework are provided in the corresponding subsections.

Sustainability Criteria and Sub-Criteria

To ensure the effective selection of WtE technologies for MSW management, it is essential to adopt a structured and sustainability-oriented framework. This study identifies multiple dimensions of sustainability to comprehensively evaluate the performance of different technologies. These dimensions reflect key aspects of sustainable development, addressing financial feasibility, environmental impacts, societal benefits, and technological performance. The framework, along with its associated sub-criteria, is summarized in Table (2) to provide a clear and systematic overview for evaluation purposes.

Table 2. Sustainability Criteria and associated Sub-Criteria for Evaluating WtE Technologies

Criteria	Symbol	Sub-Criteria	Description
Economic	S_1	Technical cost of initial investment	Expenses required for the purchase, installation, and commissioning of technology.
	S_2	Maintenance and Repair Cost	The costs necessary for operating, repairing, and maintaining the power plant [1].
	S_3	Revenue	Income generated from the sale of produced energy and recycled products [28].
Environmental	S_4	Pollutant Emissions	The amount of greenhouse gas emissions and other pollutants released into the environment.
	S_5	Soil and Water Contamination	The minimum adverse environmental impacts on soil, water and harm to the ecosystem
	S_6	Job Opportunities	The outlook for Job creation and job opportunities resulting from waste-to-energy projects [2].
Social	S_7	worker safety and health	The minimum negative effects of technology on the health and safety of the workforce, including health hazards and occupational safety.
	S_8	Impact on the Local Community	The effect of the technology on the quality of life for the local community, including minimizing odor, noise, and visual or aesthetic impacts.
	S_9	Technology complexity	The degree of complexity of technology and its need for skilled and specialized manpower [22].
Technical	S_{10}	Technological maturity	The state of technology development in the country is in a state of research or has reached a state of commercialization [2].
	S_{11}	Reliability	The ability of the technology to provide reliable services against failures, fluctuations, and ease of access to equipment.
	S_{12}	Operational Efficiency	The performance of the technology under critical conditions, such as extreme temperature fluctuations or emergency situations, and its ability to maintain optimal functionality.

The significance importance of each criterion and sub-criterion in selecting the most appropriate technologies is determined based on expert judgments.

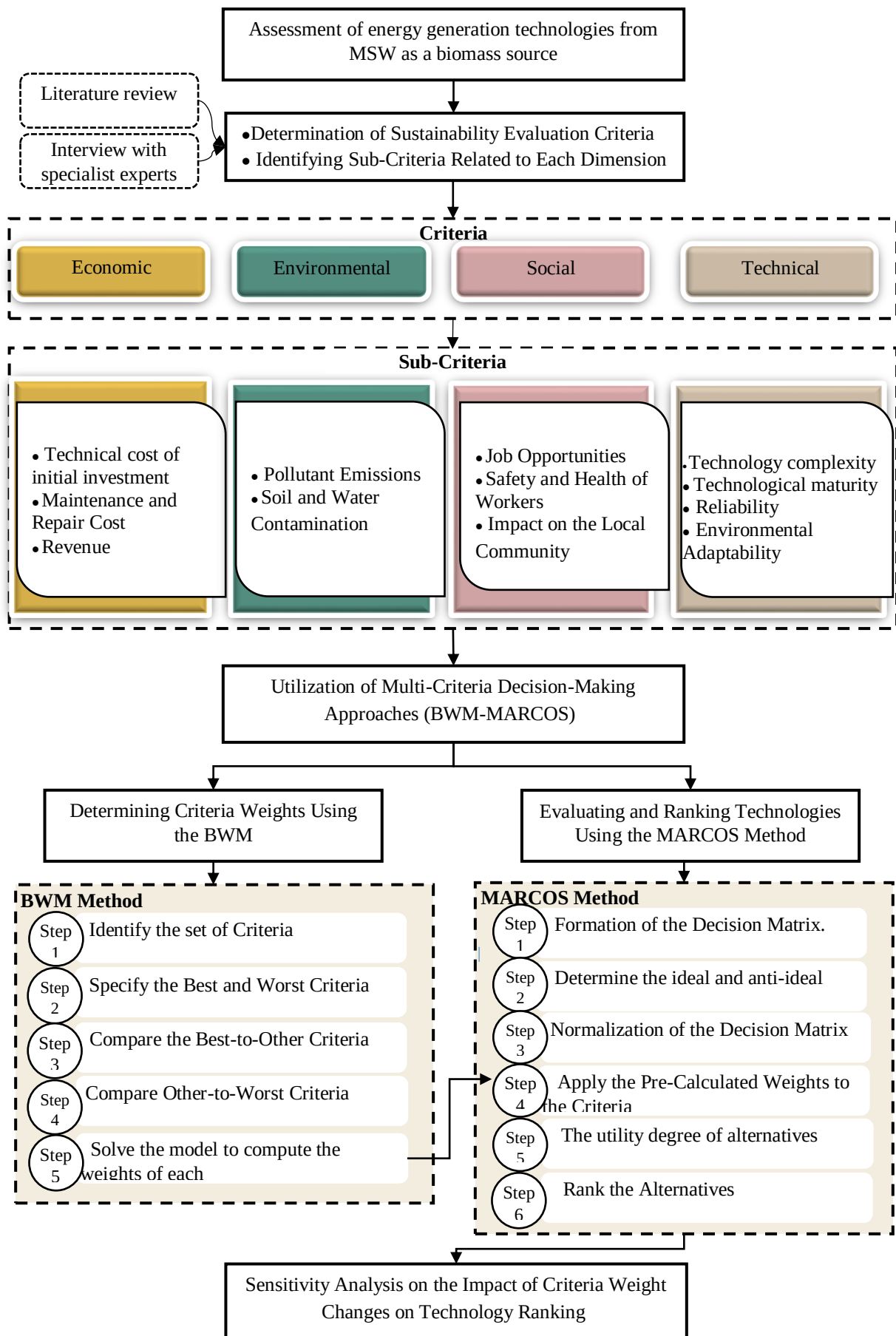


Figure 2. Methodology Framework for Evaluating WtE Technologies

Waste-to-Energy Technology Alternatives

This study focuses on evaluating six WtE technologies that are considered suitable for energy recovery from Municipal Solid Waste. The selection of these alternatives is based on a thorough review of the existing literature, consultations with experts in the fields of energy and waste management, and an analysis of the specific challenges related to energy and waste management in Iran. Given the country's heavy reliance on fossil fuels and the need for sustainable energy solutions, the emphasis was placed on selecting technologies capable of both waste management and electricity generation. The selected technologies for this study include INC, GAS, PL, LFG, PYR, and AD.

According to the Global Energy Report, WtE conversion methods are categorized into three main types: thermochemical, which uses heat to break down waste; biochemical, which utilizes biological processes to produce energy; and chemical, which relies on chemical reactions to generate energy products. The technologies used in this study are presented in Figure (3). The detailed explanations of each technology are provided in the following:

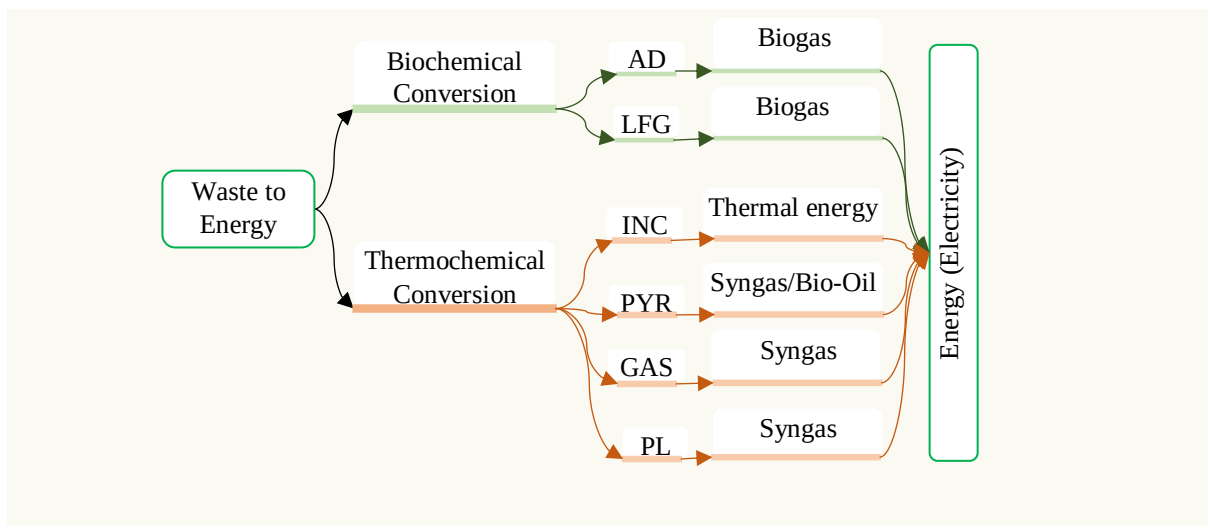


Figure 3. Waste-to-Energy Technologies

- **Anaerobic Digestion:** This biochemical process occurs within a meticulously regulated chamber known as a digester, which functions in an anaerobic environment [28]. Specialized reactors are utilized for this process, functioning under regulated conditions. Various factors, including moisture content, temperature, and pH, are carefully regulated within these reactors to create an environment conducive to microbial activity, thereby promoting their growth and accelerating the decomposition process [2].
- **Landfill Gas:** The generation of landfill gas in a sanitary landfill facility is similar to AD, yet it takes place under distinct environmental conditions [2]. When organic waste is buried in these sites, it decomposes under anaerobic conditions, producing landfill gas, mostly made up of carbon dioxide and methane. This gas contains 40 to 60 percent methane, which can be utilized as fuel to power turbines in the electricity generation process [29].
- **Incineration:** The INC process involves burning waste within a furnace under high temperatures, typically ranging from 700°C to 1400°C, with an ample supply of oxygen [1]. Controlled incineration systems, similar to fossil fuel power plants, produce electricity and heat. These systems include a waste storage chamber, incinerator, steam turbine/generator, and flue gas cleaning and waste treatment systems [29]. The flue gases are cooled in a high-pressure water feed boiler, which generates steam. This steam is then directed to a turbine, causing it to rotate. The turbine is linked to an electric generator, which produces electricity [29].
- **Pyrolysis:** PYR is a thermochemical technique that decomposes waste materials without the

presence of oxygen, employing external heating sources. In this method, heat is indirectly introduced to the waste, leading to its breakdown into smaller molecular fragments. The composition and yield of the resulting products, such as syngas, bio-oil, and char, can be influenced by regulating key parameters such as heating rate, temperature, and the duration of the process [30].

- **Gasification:** This technology is similar to pyrolysis but occurs at higher temperatures and with controlled amounts of oxygen. It is a partial oxidation process where solid waste reacts with limited oxygen at around 500°C or higher [31]. The main gasification product is syngas, which has a high thermal value and can be used for energy production [2].
- **Plasma:** Plasma, recognized as the fourth state of matter, is created by ionized gases at extremely high temperatures (1500-5000°C) using electrical discharge [2]. An electric arc generates a plasma arc, which converts organic materials into syngas and transforms inorganic materials into valuable slag [28].

MCDM Methodology

MSW management is a multidimensional decision-making challenge that requires a systematic and structured approach for evaluating WtE technologies [32]. The complexity of this process arises from the diverse and often conflicting nature of sustainability criteria, including economic, environmental, social, and technical dimensions [1, 28]. Each of these factors simultaneously influences the feasibility and effectiveness of WtE implementation. Given these complexities, MCDM methods are widely recognized as effective tools for structuring decision-making processes in various waste management systems [33].

MCDM techniques have been widely applied in various energy-related fields, including energy planning and management, resource distribution, policy-making, and structural energy management [1, 34]. In the context of MSW management, several studies have utilized MCDM for selecting WtE technologies, with some of these studies summarized in the literature review section Table 1.

According to the findings of Soltani et al., AHP has been one of the most frequently used MCDM techniques in studies involving multiple stakeholders [22]. However, AHP has certain limitations, including the need for extensive pairwise comparisons, which can make the decision-making process time-consuming and complex. Therefore, the selection of an appropriate MCDM approach should be based on the nature of the problem, the type of evaluation criteria, and the complexity of the decision-making process [21].

To address the complexity of WtE technology evaluation, this study adopts a hybrid MCDM framework that integrates the BWM for determining criteria weights and the MARCOS method for ranking WtE alternatives. The selection of this combination is based on the unique advantages of each method: BWM is an optimized technique for criteria weighting that enhances decision-making accuracy by reducing the number of pairwise comparisons and minimizing inconsistencies in expert judgments. Unlike traditional methods such as AHP, BWM follows a simplified comparative structure and employs mathematical optimization models to derive precise weights [35]. MARCOS provides a robust ranking framework by simultaneously considering both ideal and anti-ideal solutions. This feature enhances ranking accuracy and stability, particularly in studies where the evaluated technologies are influenced by fluctuating economic and environmental conditions [36].

A detailed explanation of the BWM methodology is provided in Subsection 3-3-1, while the MARCOS ranking approach is described in Subsection 3-3-2.

Best-Worst Method for Criteria Weighting

In this study, the BWM method was applied to obtain the weights of social, economic, environmental, and technical criteria, along with their twelve related sub-criteria. BWM is one

of the MCDM techniques introduced by Jafar Rezaei in 2015. This approach is useful due to its ability to reduce the inconsistency of judgments and improve the accuracy of calculating criteria weights, particularly in complex evaluations. In this process, the decision-maker determines the most favorable and most minor favorable criteria through a questionnaire and performs pairwise comparisons among these two criteria and the others. To enhance the quality of the evaluation in this research, the questionnaires were completed in collaboration with a group of experienced experts in relevant fields. The specifications of these specialists are represented in Table (3). The steps of this method are outlined below.

Table (3). Profiles of Experts Involved in Questionnaire Completion

Expert	Gender	Degree	Field	Experience (Years)
1	Male	Ph.D.	Waste Management	12
2	Female	Ph.D.	Renewable Energy Specialist	15
3	Female	Ph.D.	Industrial Engineering	19
4	Male	Ph.D.	Industrial Engineering	17
5	Male	Ph.D.	Environmental Science	26
6	Female	Ph.D.	Energy Economics	24
7	Male	M.Sc.	Energy Systems Engineering	7
8	Male	M.Sc.	Process Engineering	4

Step 1: First, a set of decision-making criteria is identified. These criteria are defined as $\{C_1, C_2, \dots, C_n\}$.

Step 2: From the predetermined set of criteria, the decision-maker selects the highest-priority criterion as the best and the lowest-priority criterion as the worst.

Step 3: The selected best criterion is compared with other criteria pairwise, and their priorities are determined using a numerical scale from 1 to 9, where 9 shows the highest priority and 1 shows the lowest priority. This comparison results in a vector called the Best-to-Others:

$$A_B = \{a_{B1}, a_{B2}, \dots, a_{Bn}\}$$

Step 4: In this step, each criterion is compared pairwise with the worst criterion, and their priorities are determined using a numerical scale from 1 to 9. This comparison generates a vector called the Others-to-Worst vector

$$A_W: \{A_{1W}, A_{2W}, \dots, A_{nW}\}$$

Step 5: After the comparisons are made, the optimal weights are obtained by solving a linear programming formulation. The Solver tool in Excel is used to solve this mathematical model, where equations (1) through (9) are used to get the final weights of the criteria.

$$z = \text{MIN } \varepsilon \quad (1)$$

$$|W_B - a_{Bj}W_j| \leq \varepsilon^* \quad \forall j \quad (2)$$

$$|W_j - a_{jW}W_W| \leq \varepsilon^* \quad \forall j \quad (3)$$

$$\sum_j W_j = 1 \quad (4)$$

$$W_j \geq 0 \quad \forall j \quad (5)$$

$$W_B - a_{Bj}W_j \leq \varepsilon^* \quad \forall j \quad (6)$$

$$-W_B + a_{Bj}W_j \leq \varepsilon^* \quad \forall j \quad (7)$$

$$W_j - a_{jW}W_W \leq \varepsilon^* \quad \forall j \quad (8)$$

$$-W_j + a_{jW}W_W \leq \varepsilon^* \quad \forall j \quad (9)$$

Note that equations (2) and (3) are nonlinear; therefore, equations (6) through (9) were utilized.

MARCOS Method

Stević and associates introduced the MARCOS technique in 2019 as an innovative MCDM method designed for assessing and prioritizing alternatives using multiple criteria. This method operates by comparing the performance of alternatives against an ideal solution (best performance) and an anti-ideal solution (worst performance). Given its capability to analyze alternatives based on various indicators and provide precise rankings, this method is employed in the present study to evaluate WtE technologies. The steps of this method are outlined below. Furthermore, in this study, the questionnaires related to the evaluation of technologies were completed by experienced experts in relevant fields. These experts include academics and professionals with years of experience in areas related to waste management technologies and environmental assessments.

Step 1. Formation of the Decision Matrix: A decision matrix is established, incorporating the alternatives and criteria under consideration. Each alternative is assessed against the specified criteria. The dimensions of the matrix are determined by the total number of alternatives (n) and criteria (m), which together constitute an $n \times m$ matrix.

Step 2. Identification of Ideal and Anti-Ideal Values: Relations (10) and (11) are utilized to define the ideal values (AI) and anti-ideal values (AAI). The term B represents the profit criteria, while C denotes the cost criteria.

$$AI = \max_i x_{ij} \text{ if } j \in B \text{ and } \min_i x_{ij} \text{ if } j \in C \quad (10)$$

$$AAI = \min_i x_{ij} \text{ if } j \in B \text{ and } \max_i x_{ij} \text{ if } j \in C \quad (11)$$

Step 3. Normalization: In this step, normalization for criteria with cost aspects and those with profit aspects is performed using equations (12) and (13).

$$n_{ij} = \frac{x_{aj}}{x_{ij}} \text{ if } j \in C \quad (12)$$

$$n_{ij} = \frac{x_{ij}}{x_{aj}} \text{ if } j \in B \quad (13)$$

Step 4. Weighting: To construct the weighted matrix, multiply the criteria weights by the normalized matrix, following equation (14) as a guideline.

$$V_{ij} = n_{ij} \times W_j \quad (14)$$

Step 5. Utility Degree of Alternatives: The ideal utility degree (K^+) and anti-ideal utility degree (K^-) for the alternatives are calculated due to equations (15) and (16). where S, as defined in equation (17), represents the aggregate of the values in each row of the weighted matrix.

$$K_i^+ = \frac{S_i}{S_{ai}} \quad (15)$$

$$K_i^- = \frac{S_i}{S_{aai}} \quad (16)$$

$$S_i = \sum_{j=1}^n V_{ij} \quad (17)$$

Step 6. Utility Function Calculation for Alternatives: Equation (18) delineates the utility function for each alternative.

$$f(K_i) = \frac{K_i^+ + K_i^-}{1 + \frac{1 - f(K_i^+)}{f(K_i^+)} + \frac{1 - f(K_i^-)}{f(K_i^-)}} \quad (18)$$

In the equation above, $f(K_i^+)$ denotes the ideal utility function, while $f(K_i^-)$ represents the anti-ideal utility function. These functions are determined using Equations (19) and (20).

$$f(K_i^-) = \frac{K_i^+}{K_i^+ + K_i^-} \quad (19)$$

$$f(K_i^+) = \frac{K_i^-}{K_i^+ + K_i^-} \quad (20)$$

Step 7. Ranking: The alternatives are ranked according to the values derived from equation (18), which represents the utility function for each option. The highest rank is given to the alternative with the highest utility function value.

Case Study

Iran holds the world's fourth-largest oil reserves and the second-largest natural gas reserves [37]. For nations with abundant fossil fuel resources and economies reliant on their export, shifting from fossil-based energy to clean energy sources poses a substantial challenge [30]. However, the extensive exploitation of these resources in recent years has led to notable environmental impacts, underscoring the necessity for a transition to renewable energy. Iran possesses significant potential for renewable energy generation, including biofuels [37]. MSW, as a rich biomass source, is available in Iran and represents an important resource for sustainable energy supply in the country.

In recent years, one of the most pressing concerns facing Iranian authorities has been the environmental damage caused by conventional waste management practices in the country. Iran is the second-largest country in the Middle East and ranks seventeenth in size worldwide, situated between latitudes 25 and 40 degrees north, a region generally classified as hot [38]. According to the widely recognized Köppen climate classification, Iran is divided into four distinct climatic zones: A) Cold, B) Temperate-humid, C) Hot-arid, and D) Hot-humid [39]. Among these four regions, the hot-arid areas cover a vast portion of Iran, encompassing approximately two-thirds of the country [40-42]. The climatic conditions of Iran are shown in Figure (1). The current study focuses on regions with a hot and dry climate.

The hot-arid climate faces specific challenges in waste management. The harsh climatic conditions in these areas reduce the facilities necessary for proper waste processing and management, increasing environmental risks such as soil pollution and unpleasant odors. Modern technologies in waste management, such as waste-to-energy conversion, can help improve waste management. Additionally, providing an alternative energy source that requires minimal water helps enhance the sustainability of energy systems and reduces pressure on water resources in these areas.

Results and Analysis

This section represents the results obtained by applying the BWM and MARCOS methods to evaluate six WtE technologies in Iran. The findings are organized into two parts. Subsection

(5-1) describes the weights of the four key sustainability dimensions and their related sub-criteria, derived using the BWM model. Subsection (5-2) provides the results of evaluating and ranking the WtE technologies using the MARCOS method based on the defined criteria. Additionally, a sensitivity analysis is conducted in Subsection (5-3) to assess the impact of weight modifications on the outcomes.

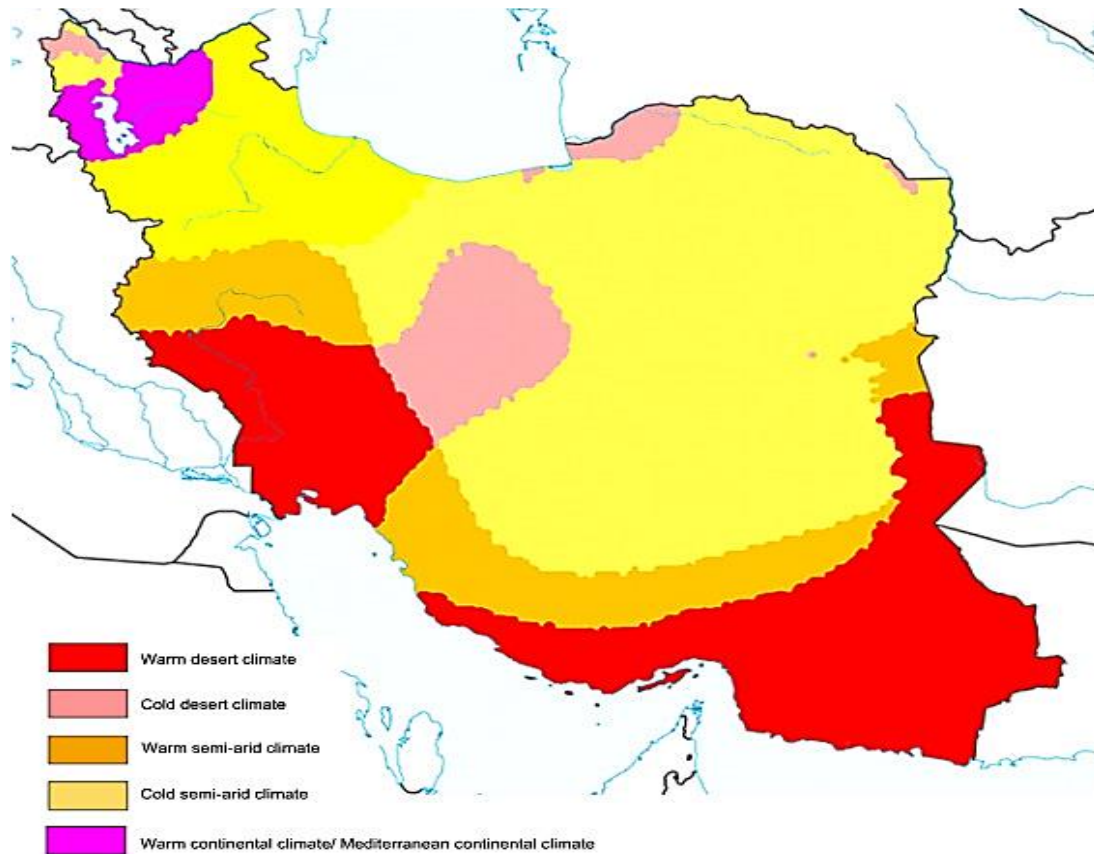


Figure 1. Climatic Regions of Iran According to the Köppen Climate Classification [28]

BWM Results

This section represents the weights of the criteria and their respective sub-criteria employed to assess WtE technologies, derived using the BWM. As detailed in Section (3-1), this weighting process was conducted based on the insights of a panel of experienced experts and specialists in the field. The results of the final weights obtained are represented in Table (4).

Table 4. Summary of BWM Results on Weights and Rankings

Criteria	Weight	Sub-Criteria	Sub-criteria weight	Total Weight	Ranking
Economic	0.491	Technical cost of initial investment	0.399	0.196	1
		Maintenance and Repair Cost	0.287	0.141	3
		Revenue	0.314	0.154	2
Environmental	0.169	Pollutant Emissions	0.693	0.117	4
		Soil and Water Contamination	0.307	0.052	9
Social	0.141	Job Opportunities	0.327	0.046	10
		Health and safety of employees	0.498	0.070	5
		Impact on the Local Community	0.175	0.025	11
Technical	0.199	Technology complexity	0.325	0.065	6
		Technological maturity	0.299	0.060	7
		Reliability	0.283	0.056	8
		Operational Efficiency	0.093	0.019	12

A graphical depiction of the criterion weights is presented in Figure (4) to illustrate the relative significance of the primary criteria in the evaluation process. This diagram helps decision-makers and readers visually discern which criteria have had the most substantial impact on the evaluation of WtE technologies in Iran. In the following, the analysis of the results is presented.

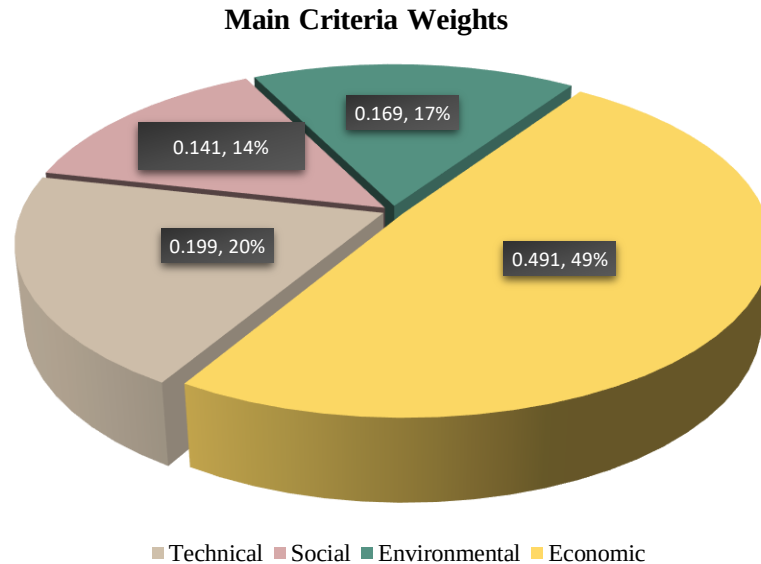


Figure 4. Weights of Sustainability Criteria

As shown in Figure (4), the results of weighting the main criteria in this study indicate that the economic criterion, with a weight of 0.491, is considered by experts as the most important factor influencing the final decision in selecting WtE technology in Iran. The significant difference in the weight of this criterion compared to others highlights the decisive role of economic considerations in countries heavily reliant on fossil fuels, such as Iran. This emphasis is due to the country's economic and energy structure, mainly focused on oil and gas resources. Therefore, any shift toward renewable energy sources must be economically justifiable to be included in national policies.

In contrast, the technical criterion, with a weight of 0.199, ranks second, emphasizing the importance of compatibility between technologies and technical requirements. However, its importance is considerably less than the economic aspect. On the other hand, social and environmental criteria, with weights of 0.169 and 0.141, respectively, have the lowest priority, reflecting less attention to social and environmental impacts in the decision-making process. These findings suggest that while social and environmental aspects are theoretically considered important, in practice, economic considerations clearly outweigh other criteria. This could hinder the achievement of sustainable goals in the development of WtE technologies. The results of the main criteria have been discussed; we will now analyze the sub-criteria to provide a clearer understanding of the significance of each. In Figure (5), the weights of the sub-criteria are presented.

From an economic perspective, the results presented in Figure (5) indicate that the technical cost of initial investment, with a weight of 0.399, is the most significant sub-criterion in selecting WtE technology. This priority underscores the significant attention decision-makers give to initial implementation costs. Following this, revenue, with a weight of 0.314, and maintenance and repair costs, with a weight of 0.287, are ranked in the subsequent positions. These results demonstrate that, in addition to initial costs, long-term economic benefits such as revenue potential and reductions in operational costs also play a crucial role in choosing the optimal technology.

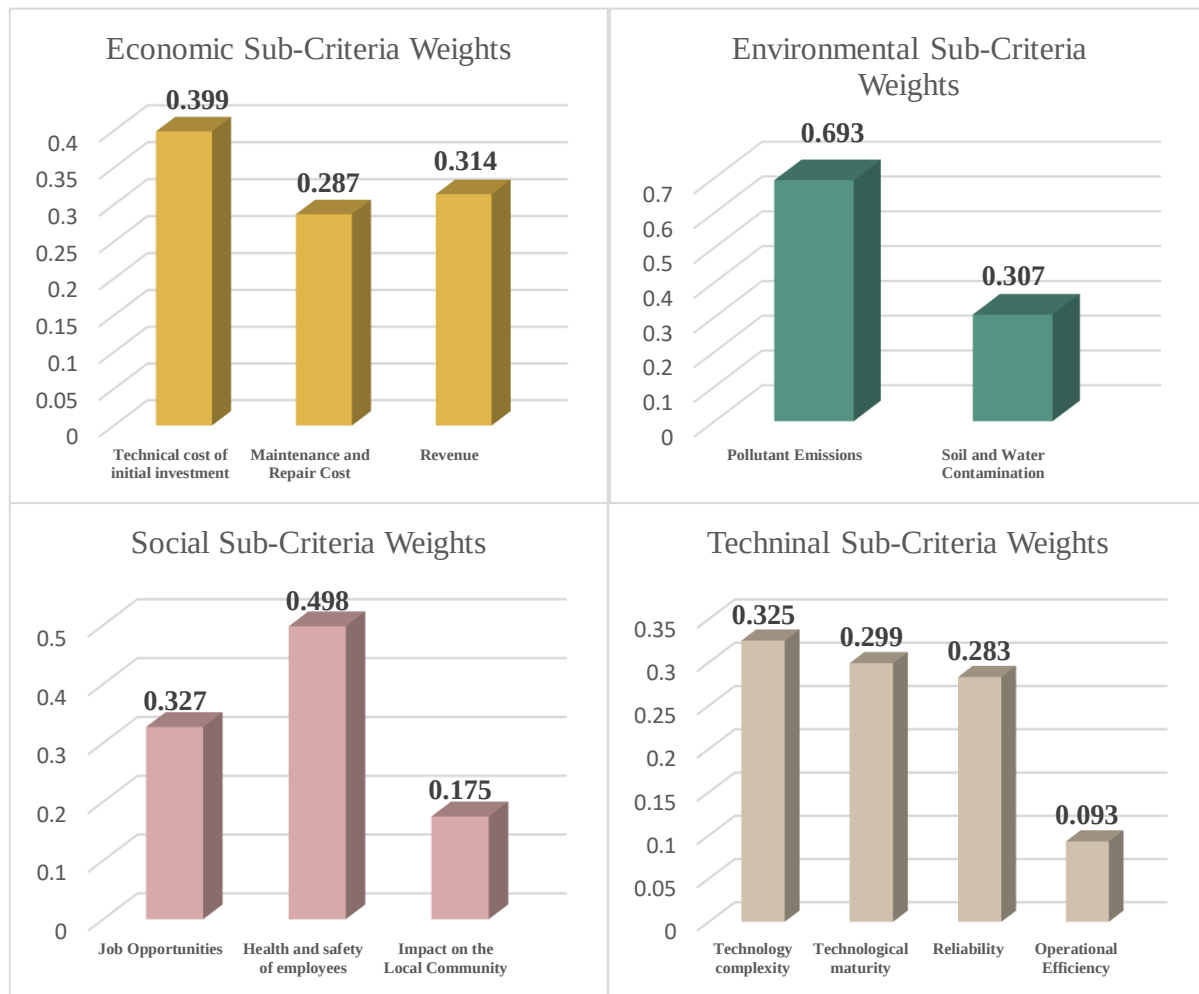


Figure 5. Weights of Sub-Criteria for Each Main Criterion

From an environmental perspective, as shown in Figure (5), the emission of pollutants, with a weight of 0.693, holds a higher priority in selecting WtE technologies compared to water and soil pollution, which weights 0.307. This study focuses on Iran's hot and dry regions, where water resources are limited and the risk of contamination is relatively low. However, the increased use of fossil fuels in recent years has not only imposed significant costs on the national economy but also intensified the air pollution crisis, particularly in urban areas. According to the Global Burden of Disease report, air pollution is the seventh leading cause of death worldwide. These challenges underscore the importance of addressing pollutant emissions and implementing effective reduction policies.

From a social perspective, the results represent that 'worker health and safety,' with a weight of 0.498, is the top priority in the selection of WtE technologies. This highlights the importance of addressing worker health in waste to energy conversion processes, as workers may be exposed to risks such as harmful chemicals and unfavorable working conditions. Following this criterion, job opportunities with a weight of 0.327, and impact on the local community with a weight of 0.175 rank next. These results highlight that, in addition to prioritizing worker safety and health, creating employment opportunities and positively influencing the quality of life in the community are also key factors in selecting WtE technologies.

From a technical perspective, the results show that 'Technology Complexity,' with a weight of 0.325, holds the highest priority in selecting WtE technologies. This highlights the crucial role that simpler technologies play in the successful implementation of waste-to-energy

conversion processes. Following this, 'Technological Maturity,' with a weight of 0.299, and 'Reliability,' with a close weight of 0.283, rank next. This suggests that decision-makers prioritize technologies that are not only reliable but also easy to implement and operate. Lastly, 'Operational Efficiency,' with a weight of 0.093, is the lowest priority.

In conclusion, Figure (6) illustrates the final priority weights of all evaluated sub-criteria for selecting WtE technology in Iran. This visual representation facilitates a quick and easy understanding of the significance of each criterion and can serve as a valuable tool for future analyses in this field.

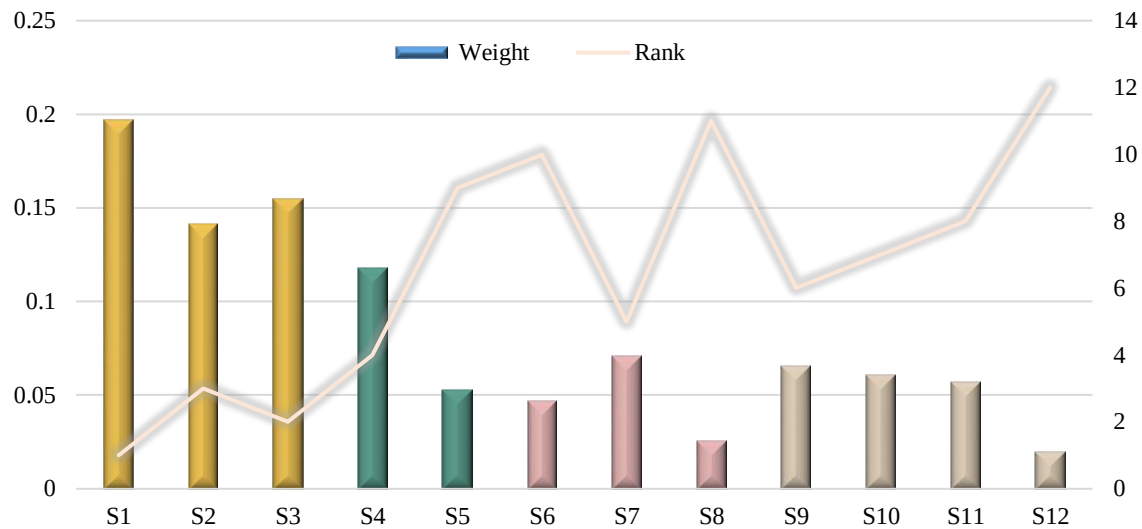


Figure 6. Overall Weights and Rankings of Sub-Criteria

MARCOS Results

The results of evaluating six WtE technologies using the MARCOS method, according to the weights obtained from the BWM approach, are examined. Table (5) shows the final utility performance and ranking of the technologies based on key indicators.

Table 5. Utility functions and final ranking

Technologies		S_i	K_i^-	K_i^+	$f(K_i^-)$	$f(K_i^+)$	$f(K)$	Ranking
A1	Incineration	0.471	2.233	0.534	0.210	0.790	0.447	4
A2	Plasma	0.551	3.325	0.796	0.210	0.790	0.522	3
A3	Pyrolysis	0.391	2.417	0.578	0.210	0.790	0.370	5
A4	Anaerobic Digestion	0.607	1.779	0.426	0.210	0.790	0.575	2
A5	Gasification	0.366	2.287	0.548	0.210	0.790	0.346	6
A6	Landfill Gas	0.666	1.787	0.428	0.210	0.790	0.631	1
AI		1						
AAI		0.265						

The results demonstrate that LFG technology, possessing the highest utility function value, is the most suitable alternative for converting MSW into energy in Iran. This technology, by collecting and purifying methane gases released from landfills, not only generates clean energy but also contributes to the reduction of greenhouse gas emissions. Other advantages of this technology include the lack of need for skilled personnel, ease of operation, and low initial investment costs. Anaerobic digestion technology ranked second, enables the biological decomposition of materials and the production of valuable by-products such as biogas and organic fertilizer. These biochemical technologies are prioritized due to their similar advantages, including low costs and more straightforward infrastructure requirements compared to thermochemical technologies, making them suitable options for developing countries with infrastructure limitations and economic constraints.

Following anaerobic digestion, thermochemical technologies—including plasma gasification, incineration, pyrolysis, and gasification—were ranked lower in the evaluation. Plasma gasification, ranked third, stands out for its ability to convert a wide range of waste materials into syngas through high-temperature processes. While this method offers high energy yields and significantly reduces waste volume, its high initial investment costs and the need for advanced technical expertise make it less suitable for developing countries like Iran, where economic and infrastructural constraints are significant.

Incineration, which ranked fourth, is a widely known technology for reducing waste volume and generating energy. Additionally, from a technical perspective, this technology is regarded as a more mature option in Iran than other newer technologies. However, the release of pollutants, such as furans and dioxins, along with the high operational costs associated with pollution control systems, limits its sustainability.

Pyrolysis, ranked fifth, produces valuable byproducts through the thermal decomposition of waste in an oxygen-free environment. Despite its potential to generate valuable by-products, its operational complexity and the need for precise temperature control make this technology less practical in areas with limited technical infrastructure. Finally, gasification, ranked sixth, also converts waste into syngas at high temperatures but faces similar challenges to pyrolysis, such as high operational costs and infrastructure requirements, making it a less attractive option for resource-constrained countries.

The prioritization of these technologies is directly influenced by the evaluation criteria weights, which were determined using the BWM approach. The economic criterion, with a weight of 0.491, emerged as the most significant factor in ranking the technologies. In a country like Iran, where access to fossil energy resources such as gas and oil is relatively easy and cost-effective, the selection of technologies that require lower initial investments can be entirely justified. This is consistent with the results, as landfill gas recovery and anaerobic digestion—ranked first and second, respectively—are both classified as biochemical technologies. These technologies offer a greater economic advantage due to their lower costs compared to thermochemical alternatives.

Sensitivity Analysis

This section first examines the effect of different weight distributions Section 5.3.1 and then compares the rankings using alternative MCDM methods to validate consistency Section 5.3.2.

Sensitivity Analysis of Criteria Weighting

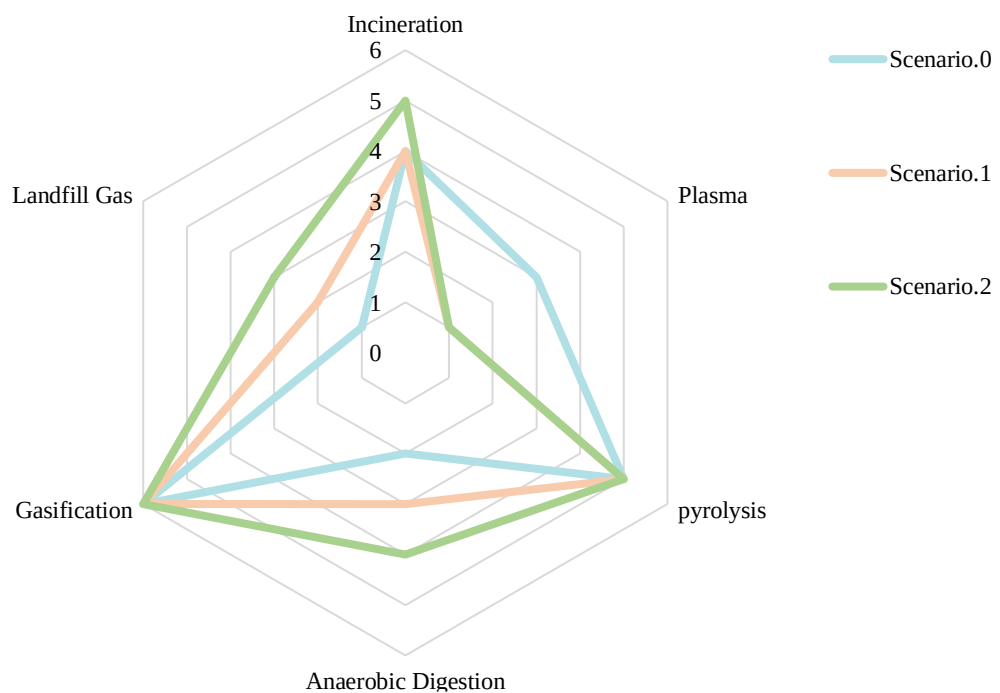
The prioritization of WtE technologies was carried out using the criteria weights derived through the BWM method, and the direct impact of these weights on the ranking of technologies is evident. Since no single technology holds a definitive superiority over others, adjustments in the weighting of criteria can substantially influence the final outcomes. Sensitivity analysis is essential for evaluating how shifts in these weights impact the overall ranking of alternatives. In this study, particular emphasis was placed on the economic criterion due to its significance. Therefore, the sensitivity analysis examined how fluctuations in its weight—whether increased or decreased—could potentially reshape the ranking of various technologies.

To this end, two scenarios were considered. In scenario zero, the weights of all four sustainability dimensions were assigned according to the original values determined by the BWM method. In the first scenario, the weights of all four dimensions were assigned equally at 0.25 to analyze the impact of uniform weight distribution. In the second scenario, the weight of the economic criterion was reduced to 0.1, while the weights of the other three criteria were set equally at 0.3. These scenarios allow us to observe the effects of reducing the weight of the economic criterion and increasing the significance of other criteria in the final ranking of technologies. The results of this analysis are represented in Table (6).

Table 6. Sensitivity Analysis Results for WtE Technology Ranking

Sensitivity analysis	Criteria	Criteria Weight	WtE Technologies	Ranking
Scenario.0			Incineration	4
	Economic	0.491	Plasma	3
	Environmental	0.169	pyrolysis	5
	Social	0.141	Anaerobic Digestion	2
	Technical	0.199	Gasification	6
			Landfill Gas	1
Scenario.1			Incineration	4
	Economic	0.250	Plasma	1
	Environmental	0.250	pyrolysis	5
	Social	0.250	Anaerobic Digestion	3
	Technical	0.250	Gasification	6
			Landfill Gas	2
Scenario.2			Incineration	5
	Economic	0.100	Plasma	1
	Environmental	0.300	pyrolysis	5
	Social	0.300	Anaerobic Digestion	4
	Technical	0.300	Gasification	6
			Landfill Gas	3

As explained, the prioritization of the economic criterion significantly influenced the results. In Iran, considering the vast oil and gas reserves, the high importance of the economic criterion in selecting WtE technology is entirely justified, as accessing fossil energy is easier and more cost-effective. In both scenarios, it was found that if the economic dimension is less important, the optimal choice shifts toward plasma technology, which performs well in terms of energy efficiency and pollutant reduction. Therefore, it is essential to also consider social and environmental dimensions when selecting WtE technologies in Iran, reducing the excessive reliance on economic factors. This approach promotes more sustainable and effective implementation of these technologies, contributing to a balance between economic development and environmental sustainability while enhancing the country's waste management system. Figure (7) presents a comparative analysis of the selected WtE technologies across several scenarios.

**Figure 7.** Comparison of WtE Technologies Based on Scenarios

The emergence of plasma as the top-ranked technology in both Scenario 1 and Scenario 2 highlights the influence of environmental, social and technical factors when economic considerations are deprioritized. Unlike conventional WtE methods, plasma gasification achieves higher thermal efficiency and significantly reduces toxic emissions, such as dioxins and heavy metals. Additionally, its ability to produce high-purity syngas enhances energy recovery potential while minimizing waste residue.

These attributes make plasma gasification a more favorable option in sustainability-driven decision contexts. While its high capital costs may limit adoption in developing economies, prioritizing long-term environmental benefits and public health considerations strengthens its viability in future waste management strategies.

Validation Using Hybrid MCDM Models

To ensure the robustness and reliability of the ranking results, a comparative analysis was conducted using alternative MCDM methods. While the MARCOS method was initially employed to rank WtE technologies, additional validation was performed by applying the ARAS and SAW methods to the same dataset. Employing multiple MCDM methods enhances result reliability by reducing the potential biases associated with a single method and ensuring methodological robustness. Table 7 provides a comparative overview of the three MCDM methods—MARCOS, ARAS, and SAW—highlighting their computational complexity and decision-making suitability.

Table 7. Comparison of MCDM Methods

Method	Computational Complexity	Decision-Making Suitability
MARCOS	incorporates ideal and anti-ideal solutions	Suitable for complex sustainability assessments with multiple criteria
ARAS	evaluates alternatives based on a reference point	Effective for comparing technologies against a predefined ideal
SAW	aggregates weighted criteria into a single score	Best suited for straightforward decision-making with fewer alternative

To further validate the consistency of the ranking results, the final scores and rankings obtained from MARCOS, ARAS, and SAW are presented in Table 8. The results indicate that all WtE technologies received identical rankings across the three methods, demonstrating a high level of methodological stability.

Table 8. Final Scores and Ranking Results of WtE Technologies Using MARCOS, ARAS, and SAW

Alternatives	MARCOS	Rank	ARAS	Rank	SAW	Rank
	$f(K_i)$		K_i		S_i	
Incineration	0.447	4	0.364	4	0.433	4
Plasma	0.522	3	0.522	3	0.589	3
Pyrolysis	0.370	5	0.336	5	0.406	5
Anaerobic Digestion	0.575	2	0.525	2	0.602	2
Gasification	0.346	6	0.295	6	0.358	6
Landfill Gas	0.666	1	0.657	1	0.628	1

For better visualization and interpretation, Figure 8 illustrates the ranking results derived from the three MCDM methods, further substantiating the consistency of the findings.

Practical Discussions and Managerial Insights

The main practical discussions and managerial insights of the proposed integrated approach and analyses are as follows:

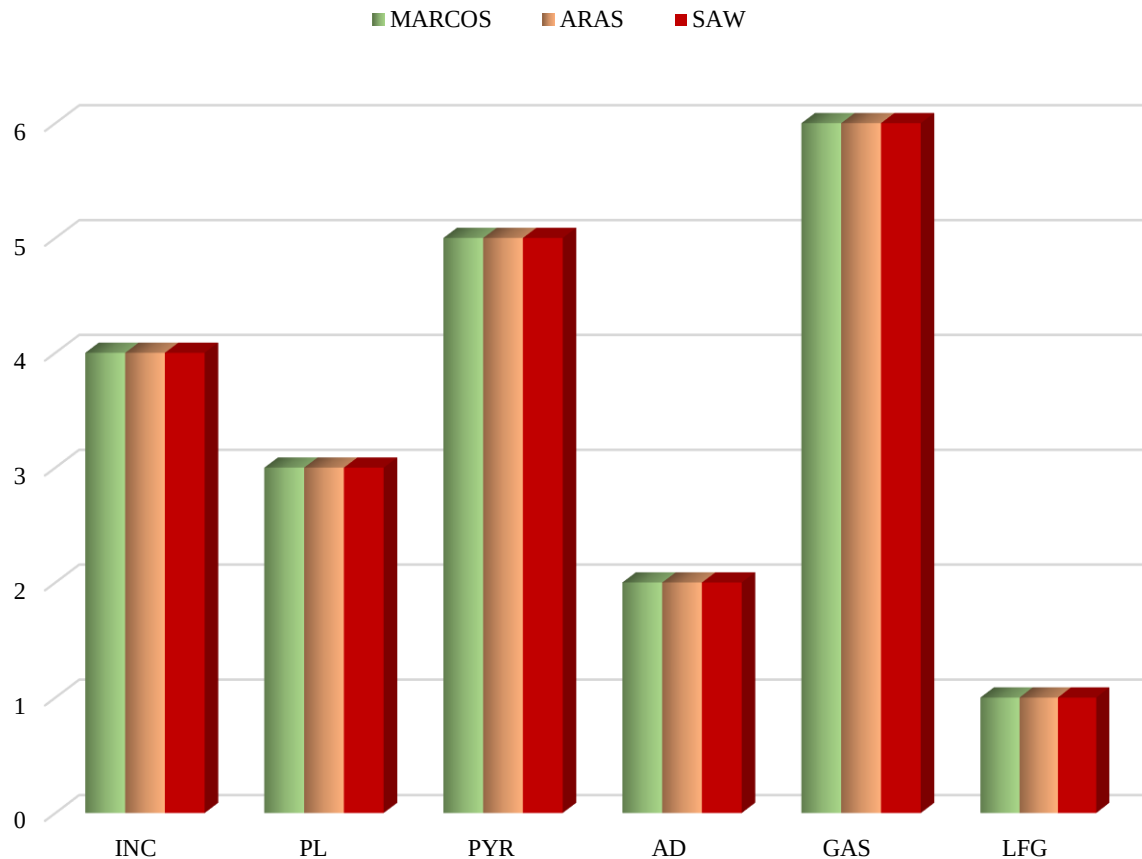


Figure 8. Comparative Analysis of MCDM Rankings for WtE Technologies

Key Managerial Insights

- A. Prioritizing Economic Feasibility:** The study highlights the importance of economic considerations in selecting WtE technologies, particularly in fossil fuel-dependent economies like Iran. Managers should prioritize technologies with lower initial investment and operational costs, such as landfill gas and anaerobic digestion, to ensure financial viability and smoother implementation in constrained economic environments.
- B. Integration of Sustainability in Decision-Making:** Incorporating sustainability into WtE technology selection is crucial for long-term success. Managers should evaluate technologies not only based on economic performance but also on environmental, social, and technical factors, ensuring a balanced approach that aligns with corporate social responsibility and sustainability goals.
- C. Technology Adaptation to Local Conditions:** The findings suggest that biochemical technologies (like AD and LFG) are more suited to Iran's infrastructure and economic context. Managers should focus on technologies adaptable to local climatic, environmental, and infrastructural conditions to minimize risks and enhance operational efficiency.
- D. Developing Technical and Human Resources:** Advanced thermochemical WtE technologies, such as plasma and gasification, require specialized technical expertise and infrastructure. Managers should invest in capacity building, technical training, and partnerships to gradually introduce these technologies, particularly for regions aiming to adopt more advanced waste management solutions.

Regulatory Framework and Policy Challenges for WtE Development in Iran

The development of WtE in Iran is influenced by a combination of regulatory policies,

financial incentives, and institutional challenges. While WtE has been recognized as a potential solution for MSW management and renewable energy generation, its deployment remains limited due to regulatory and economic challenges.

A. Financial Incentives and Feed-in Tariffs (FiT)

Iran has introduced FiT for renewable energy, including WtE, to encourage private sector participation. However, the FiT rates for WtE remain significantly lower than those offered for solar and wind energy, reducing the attractiveness of investment in this sector.

B. Weak Waste Management Regulations and Infrastructure

One of the primary obstacles to WtE development in Iran is the lack of nationwide waste separation at the source. The high organic content and moisture levels in MSW significantly impact the efficiency of incineration and gasification technologies. Moreover, there is no cohesive national waste management strategy, leading to fragmented implementation across different provinces.

C. Environmental Regulations and Project Approval Barriers

WtE projects in Iran must undergo rigorous environmental impact assessments to receive approval. While these regulations are essential for ensuring sustainability, lengthy bureaucratic processes and public opposition to certain WtE technologies has further complicated their deployment.

D. Emerging Policy Developments and Future Outlook

In recent years, pilot WtE projects have been initiated, particularly in provinces like Yazd, where pyrolysis-based WtE facilities are being tested. However, for large-scale adoption, Iran needs to reform its regulatory framework, enhance financial incentives, and improve MSW management practices to align with global best practices.

Conclusion and Future Works

Waste management and sustainable energy supply are among the fundamental challenges facing developing countries, particularly Iran. This research, adopting a sustainable development approach, evaluated six different WtE technologies for managing MSW. The findings show that the economic criterion has received the most attention in the selection of WtE technologies, largely due to Iran's economic and energy structure, which is heavily reliant on oil and gas resources. As such, any transition to renewable energy sources must be economically justifiable to be integrated into national policies.

Given the significant influence of economic factors, two biochemical technologies—landfill gas recovery and anaerobic digestion—were ranked first and second, respectively. These technologies are more attractive due to their lower costs and high efficiency in recovering energy from waste, making them practical solutions for improving waste management and ensuring a sustainable energy supply in Iran. In contrast, thermochemical technologies, such as plasma gasification, which ranked third, offer high energy efficiency and significantly reduce waste volume by converting a wide range of waste materials into syngas through high-temperature processes. However, their high initial investment costs and the need for advanced technical expertise make them less viable for developing countries like Iran, where economic and infrastructural constraints prevail.

Thus, it is recommended that policymakers in Iran prioritize the development and promotion of biochemical technologies, which are more economically viable and can contribute to effective waste management and a sustainable energy supply. Additionally, to support the future adoption of advanced thermochemical technologies, attention should be given to strengthening educational and technical infrastructure. This approach can enhance energy efficiency, reduce the environmental impacts of inefficient waste management, and help Iran

progress toward its sustainable development goals.

To further strengthen the practical applicability of WtE projects in Iran, future research should place greater emphasis on policy, regulatory, and institutional challenges affecting their implementation. The development of comprehensive legislative frameworks, including mandatory waste separation programs, clear financial incentives, and streamlined project approval processes, is crucial to accelerating WtE adoption. Additionally, further studies could explore the impact of policy consistency and long-term governmental commitments in fostering private-sector participation and ensuring the economic viability of WtE investments. Addressing these regulatory gaps would provide a more holistic foundation for integrating WtE into Iran's national renewable energy strategy.

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