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RESEARCH PAPER

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 DIxetr 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
Social	S_6	Job Opportunities	The outlook for Job creation and job opportunities resulting from waste-to-energy projects [2].
	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.
Technical	S_9	Technology complexity	The degree of complexity of technology and its need for skilled and specialized manpower [22].
	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.

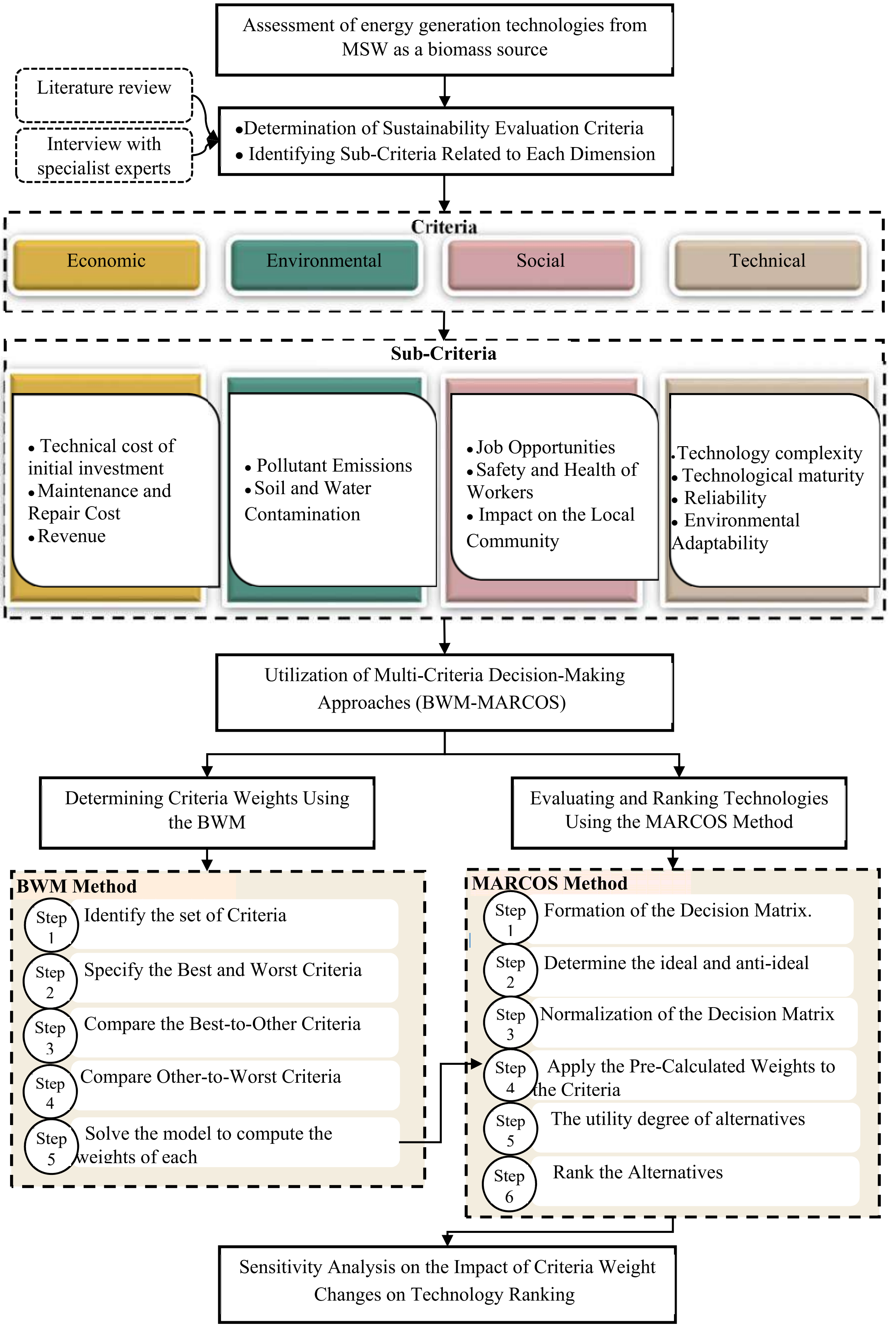

Figure 2. Methodology Framework for Evaluating WtE Technologies

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