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RESEARCH ARTICLE **RENEWABLE ENERGY**

Waste Management Solutions for Tunisia: An MCDM Analysis of Energy-from-Waste Technologies

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ABSTRACT

Conventional waste management practices, such as landfilling and uncontrolled dumping, pose increasing environmental and sustainability challenges, particularly in developing countries. Energy-from-waste (EfW) technologies offer an alternative by converting municipal solid waste into useful forms of energy, including electricity and heat. However, selecting the most suitable technology requires balancing technical, economic, environmental, and social factors. This study applies a multi-criteria decision-making (MCDM) framework that combines Grey System Theory with the Additive Ratio Assessment (ARAS) method to evaluate and rank seven EfW technologies in Tunisia. Grey analysis was used to determine the relative weights of ten evaluation criteria, while the ARAS approach was employed to assess alternatives, including anaerobic digestion, depolymerization, gasification, incineration, landfill gas recovery, plasma gasification, and pyrolysis. The results indicate that landfill gas recovery is the most suitable option under current conditions, followed by anaerobic digestion, while plasma gasification ranks lowest. These findings highlight the importance of cost and operational feasibility in technology selection. The study concludes that prioritizing landfill gas and anaerobic digestion could support sustainable waste management in Tunisia, although literature-based data and expert judgment influence the results. Future work incorporating site-specific data and broader stakeholder input could further improve decision robustness.

حلول إدارة النفايات في تونس: تحليل تقنيات تحويل النفايات إلى طاقة باستخدام منهجية اتخاذ القرار متعدد المعايير

ساسي الرقيق [1,*]، سناء صالحي [2] ، دلمريا ريتشارد [3]، جونسون منساه [4] ، هالة جارالله الخزندار [5] ، ياسر فتحي نصار [6]

الملخص

تُشكّل الممارسات التقليدية لإدارة النفايات، مثل الطمر في المكبّات والتخلّص العشوائي منها، تحديات بيئية متزايدة تُهدّد تحقيق أهداف الاستدامة، ولا سيّما في البلدان النامية . وفي هذا السياق، تُمثّل تقنيات تحويل النفايات إلى طاقة بديلاً واعداً، إذ تتيح تحويل النفايات الصلبة البلدية إلى أشكال مفيدة من الطاقة، بما في ذلك الكهرباء والحرارة. غير أنّ اختيار التقنية الأنسب يستلزم تحقيق توازن بين مجموعة من العوامل التقنية والاقتصادية والبيئية والاجتماعية. تهدف هذه الدراسة إلى تطبيق إطار منهجي لاتخاذ القرار متعدد المعايير، يجمع بين نظرية الأنظمة الرمادية وطريقة التقييم وفق النسب المضافة، بهدف تقييم سبع تقنيات لتحويل النفايات إلى طاقة وترتيبها وفقاً لمدى ملاءمتها للتطبيق في تونس. وقد استُخدم التحليل الرمادي لتحديد الأوزان النسبية لعشرة معايير تقييم، في حين اعتُمدت طريقة لتقييم البدائل التقنية، التي تشمل الهضم اللاهوائي، وإزالة البلمرة، والتغويز، والحرق، واسترداد غاز المكبّات، والتغويز بالبلازما، والتحلل الحراري. وأظهرت النتائج أنّ تقنية استرداد غاز المكبّات تُعدّ الخيار الأكثر ملاءمة في ظل الظروف الراهنة، تلها تقنية الهضم اللاهوائي، في حين جاءت تقنية التغويز بالبلازما في المرتبة الأخيرة. وتُبرز هذه النتائج الأهمية المحورية للتكلفة والجدوى التشغيلية في تحديد التقنيات الأكثر ملاءمة. وخلصت الدراسة إلى أنّ إعطاء الأولوية لتقنيتَي استرداد غاز المكبّات والهضم اللاهوائي من شأنه أن يدعم التحوّل نحو إدارة مستدامة للنفايات في تونس، مع الإقرار بتأثّر النتائج بالبيانات المستمدة من الأدبيات العلمية والأحكام التقديرية للخبراء. كما توصي الدراسة بأن تتناول البحوث المستقبلية دمج بيانات ميدانية خاصة بمواقع التطبيق، إلى جانب توسيع مشاركة الجهات المعنية في عملية التقييم، بما يُعزّز متانة القرارات وموثوقية النتائج.

الكلمات المفتاحية

إدارة النفايات المستدامة
تحويل النفايات إلى طاقة
اتخاذ القرار متعدد المعايير
نظرية الأنظمة الرمادية
طريقة التقييم وفق النسب المضافة

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Introduction

Global municipal solid waste (MSW) generation continues to grow, driven by steady population growth, rising urbanization and industrial activity, and changing consumer behavior [1–4]. The world produced an estimated 2.3 billion tons of municipal solid waste t the end of 2025. If waste production follows the same trajectory as it does now, it will be estimated at over 3.8 billion tons by 2050 [5]. Per-person waste generation is expected to increase from an average of 1.2 kg per day to about 1.5 kg per day in the near future [6,7]. Unless effective methods for managing this trend are developed, it will continue to pose risks to environmental health, human well-being, and energy security.

In many regions, especially developing countries, landfilling remains the predominant disposal method. However, declining availability of suitable land and increasing environmental concerns have underscored the urgency of adopting alternative waste management strategies [8,9]. Energy-from-Waste (EfW) systems are gaining prominence as they can both reduce waste volume and generate energy [10–12]. These technologies include incineration, gasification, pyrolysis, anaerobic digestion, depolymerization, landfill gas recovery, plasma arc gasification, and hydrothermal carbonization.

In developing nations, however, several challenges impede the deployment of EfW equipment. These include high capital requirements, technical complexity, limited institutional capacity, and the absence of robust policy frameworks. Tunisia exemplifies this problem. In 2024, household waste generation reached 2.62 million tons (Fig. 1), with the urban per capita generation increasing from 0.8 kg/day in 2012 to 1.28 kg/day. Rural areas produce significantly less, at approximately 0.18 kg/day [13]. Additional annual waste streams include 150,000 tons of industrial waste, 60,000 tons of packaging waste, 18,000 tons of healthcare waste, and approximately 5 million tons of phosphogypsum, which poses considerable environmental challenges [13, 14].

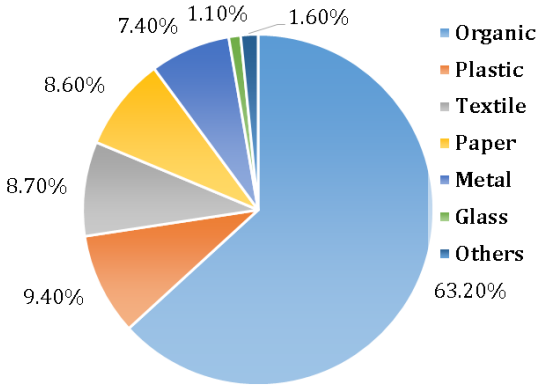


Figure 1: Household and similar waste compositions in Tunisia

Currently, approximately 70% of Tunisia's waste is disposed of in controlled landfills, while 21% is dumped in unregulated or illegal dumpsites [15]. Composting and recycling rates are extremely low: approximately 5% is composted, and 4% is recycled. Economic constraint and lack of effective institutional capacity, as well as poor governance, have created an environment that supports increased illegal dumping, which creates additional health risks and ecological hazards and puts further pressure on governmental agencies to comply with the constitutional mandate to protect citizens' rights to a safe, clean, and healthy environment [16, 17].

Adopting energy-from-waste (EfW) could have several positive impacts, including reducing greenhouse gas emissions, increasing energy security, and providing employment opportunities [18–22]. However, several barriers make it difficult to deploy EfW technology on a widespread scale, notably high costs, stringent emission control requirements, and public acceptance concerns [23–25].

Therefore, determining a feasible EfW technology requires a multidimensional analysis of each alternative, given significant differences in relative technical efficiency, economic feasibility, environmental impact, and social acceptance. In this context, applying multi-criteria decision-making (MCDM) techniques provides an objective method for evaluating options based on multiple criteria and stakeholder preferences [21]. The Additive Ratio Assessment (ARAS) method, combined with Grey System Theory, is used in this paper to rank various EfW technologies in Tunisia by priority. Using ARAS allows for a weighted rating of each criterion and a ranking of each option to identify which option offers the most sustainable technology solution in the Tunisian environment.

2. Energy-from-Waste technologies

EFW technologies play a vital role in the waste hierarchy because they can convert municipal solid waste into useful energy products, thereby providing economic and environmental benefits by reducing dependence on fossil fuels and delivering significant economic and environmental benefits [21, 26–28]. The primary environmental contributions include GHG reductions, reduced landfill use, and protection of soil and groundwater [29-31]. There are two main pathways for converting MSW to energy: biochemical and thermochemical. The preferred methods are thermochemical because of their superior conversion efficiency, faster processing times, better cost-effectiveness, and the ability to treat various feedstocks [31, 32]. Table 1 summarizes the major EfW technologies examined in this paper, along with their typical configurations and operational conditions.

Incineration

Thermal treatment methods of incinerating combustible components of MSW to recover energy have been well established in practice for many years. The typical operating temperature of this technology is above 850°C. At such temperatures, the entire organic content of the waste is completely oxidized by air during combustion. All that remains after the combustion process is carbon dioxide and water vapor. Thermal treatment processes also provide a significant reduction in waste mass (up to 90%), allowing heat generated by combustion to be recovered and used directly or converted to electrical energy [37].

Incinerating waste is intended to maximize the oxidation of the combustible components of waste (carbon, sulfur, etc.) with oxygen at elevated temperatures, so the chemical potential of those components is converted into thermal energy, as noted in [2]. Waste material consisting primarily of plastics, paper, and rubber has substantial caloric content. That caloric content produced during this conversion can be converted to electricity. There are three basic steps involved in the process: combustion of MSW in air, recovery of energy from the hot gas produced by combustion, and emission control, which ensures that the combustion process is environmentally acceptable [39]. A schematic representation of a standard MSW incineration system is shown in Fig. 2.

Table 1: Specifications and operating conditions of EfW technologies [30–34]

Technology	Process type	Operating temp (°C)	Residence time	Feedstock type	Efficiency	Cost	Products
Incineration	Thermo-chemical (complete oxidation)	800-1400	Seconds-minutes	Biological and synthetic origin dry wastes	50-60%	Medium–high	Heat, Ash
Gasification	Thermo-chemical (partial oxidation)	500-1300	0.5-1 h	Dry mixed MSW without inorganic materials	70-80%	High	Char, Syngas
Pyrolysis	Thermo-chemical (oxygen absence)	400-1000	Seconds–weeks	Dry mixed MSW without inorganic materials	70%	High	Syngas, oxygenated oils, char
Plasma Arc Gasification	Thermo-chemical (partial oxidation)	1500-5000	-	Any wasteage	90%	Very high	Solid slag, syngas prime gas producer
Landfilling	Biochemical (oxygen absence)	35-60	-	MSW with a high organic matter	50-85%	-	Landfill gas
Thermal depolymerization	Thermo-chemical	200-500	-	Wet mixed organic waste	85%	High	Clean-burning gas, high-quality oil, and solid minerals
Anaerobic Digestion	Biochemical (oxygen absence)	25-60	15-30 days	Organic waste without metals and plastics	50-70%	Medium–high	Sludge, Methane, Other gases

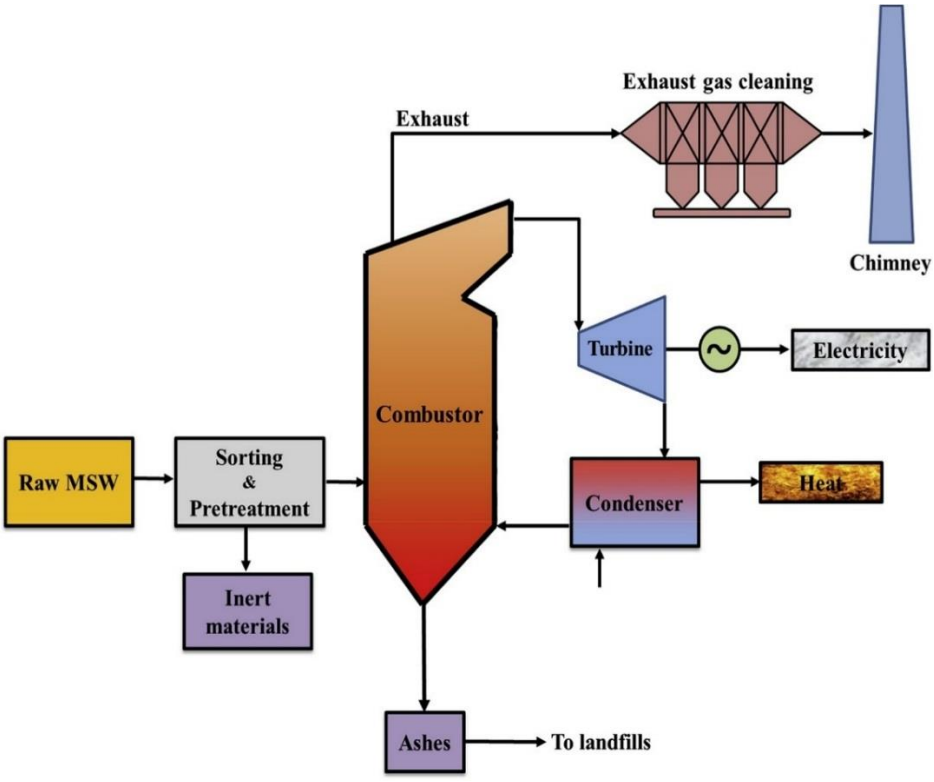


Figure 2: Network with eight vertices [37].

Gasification

Gasification is a thermal-chemical process for EfW that is widely used for MSW management [40]. The gasification process heats MSW under reduced-oxygen conditions [37] and, through several chemical processes, converts the organic portion of MSW into useful energy forms. The conversion of all types of solid, semi-solid, and liquid materials into synthesis gas is achieved through gasification [41]. Synthesis gas is a versatile, clean fuel that can be converted into a range of products, including electricity, hydrogen, methanol, and natural gas. As a direct result of the gasification process, synthesis gas is composed of CO, H_2, CH_4, CO_2, and trace amounts of lighter hydrocarbon compounds, including ethane, ethene, and ethylene [42]. Due to its high calorific value, the synthesis gas produced can be used as an economical source of heat and power [37].

The gasification process takes place at high temperatures, approximately 800 °C, and yields up to 85% of gaseous products. The energy produced by this process can be used directly. Nevertheless, several parameters determine both the efficiency and yield of this process. Examples include particle size of raw materials, reaction temperature, moisture

content, heating rate, and the process technique. Additionally, the type of agent used in the gasification process is considered an important factor [31, 32]. A gasification system consists of three major components: the gasifier, which produces combustible gas, the cleaning system, which removes undesired or harmful components from the gas, and the energy recovery system, which uses the gas to generate energy [39].

2.3 Pyrolysis

Pyrolysis is a thermal decomposition process carried out in an inert atmosphere to convert biomass into higher-value-added products [43]. Raclavska et al. [44] highlight that this process consists of the thermochemical decomposition of carbonaceous materials in the absence of oxygen or other reagents, resulting in the production of synthesis gas (a mixture of CO, H_2, CO_2, and CH_4), as well as solids (coal) and liquids (oxygenated oils). Product yields and quality depend on operating temperature, heating rate, residence time, feedstock composition, and particle size [17,45].

The process is commonly classified into:

- ✓ Slow pyrolysis, also known as traditional pyrolysis, produces mainly char and tar at ~550 °C over extended residence times, with raw material heating rates of 0.1-2 °C/s [33].
- ✓ Intermediate pyrolysis is optimized for bio-oil yields at moderate temperatures and short to medium processing times.
- ✓ Fast pyrolysis, which involves high heating rates, produces bio-oil rapidly at 586–977 °C.
- ✓ Flash pyrolysis, which involves extremely high heating rates at >1000 °C, produces high-quality gaseous products in the range of 105°C/s to 200°C/s. However, because the products of fast pyrolysis resemble fossil fuels, it is the most widely used technology in practice [33].

A comparison of operational parameters for each type is given in Table 2.

Table 2: Main parameters of the pyrolysis process [17, 35, 39]

Parameters	Slow pyrolysis	Intermediate pyrolysis	Fast pyrolysis	Flash pyrolysis
Feedstock	Algal biomass	Biomass feedstock	Lignocellulosic and wood waste	Wood sawdust
Temperature (ºC)	550–900	300–500	500–1250	1050–1300
Heating rate (K/s)	<1	30-1500	500–10^5	>10^5
Particle size (mm)	5–50	No limit requirement	<1	<0.2
Residence time (s)	300–3600	2-4	0.5–10	<0.5
Outcomes	Bio-oil (20–50%); Gas (20-50%); Biochar (25–35%)	Biochar (16–25 %); Bio-oil (40–60 %); Gas (20–30 %)	Biochar (15 %); Bio-oil (70 %); Gas (15 %)	Bio-oil (60–75 %); Biochar (10–25 %); Gas (10–30 %)

Plasma Arc Gasification

Among thermal conversion techniques for waste, plasma gasification stands out as one of the cleanest options for EfW conversion, and it is widely recognized as a promising approach in several scientific publications [46]. The main advantage of this technique lies in its ability to treat waste safely while generating renewable energy efficiently and in an environmentally sustainable manner [47]. The plasma arc gasification process is considered highly innovative, as it can handle varied and complex waste streams and efficiently produces energy-rich synthesis gas, also known as "syngas," along with an inert vitrified slag. The high temperatures between 3,400 and 7,000 °C ensure the complete breakdown of complex organics and hazardous substances [48]. Fig. 3 shows a typical plant layout for MSW treatment by plasma gasification.

In the gasification/vitrification furnace, high temperatures ensure the rapid and complete decomposition of the organic compounds in the waste, producing significant volumes of combustible gases. These high temperatures are achieved by thermal plasma generators, which, in modern applications, use plasma torches. Such devices conduct electric current through a gaseous medium, such as air, generating electrical discharges due to the potential difference between two electrodes. This creates a plasma arc, converting the gas into a plasma state [48]. The resulting synthesis gas, formed from the organic fraction of the waste, concentrates much of the heat and chemical energy of the treated materials. This gas can be used to generate energy and to produce various useful products, such as transportation fuels [31].

High temperatures in the gasification/vitrification furnace ensure rapid, complete disintegration of the biodegradable waste, producing large amounts of combustible gases. High temperature is achieved using Thermal Plasma Generators, in which the plasma torch has been used recently. A potential difference is created across two electrodes when an electrical current flows through a gaseous medium (for example, air) in this system; consequently, discharges occur. As a result, the plasma arc forms in the gas and converts it to a plasma state [48]. The syngas resulting from processing the organic components of waste will contain a significant amount of the heat and chemical energy of the processed materials. Afterward, the syngas may be used to generate electricity or converted into other high-value products, such as transportation fuel [31,32].

Landfilling

The disposal of MSW in landfills remains the most widely used traditional method [50]. Biogas can be extracted from both digesters and anaerobic reactors, as well as from landfills. In landfills, biogas, known as landfill gas (LFG), is generated by the anaerobic decomposition of MSW [31,37,51]. This gas can be captured, converted, and used as an energy source, provided that an adequate collection and management system is implemented. However, biogas produced in landfills is not always of high quality due to low methane (CH4) concentrations and the presence of corrosive compounds such as hydrogen sulfide (H_2S) [52]. Biogas generally comprises 50-70% CH4 and 30-40% carbon

dioxide (CO2), along with residual biodegradation byproducts such as ammonia (NH_3) and H_2S [53]. The efficiency and composition of biogas produced in landfills are influenced by factors including temperature, toxins, moisture content, pH, and reduction-oxidation (redox) potential [21, 54].

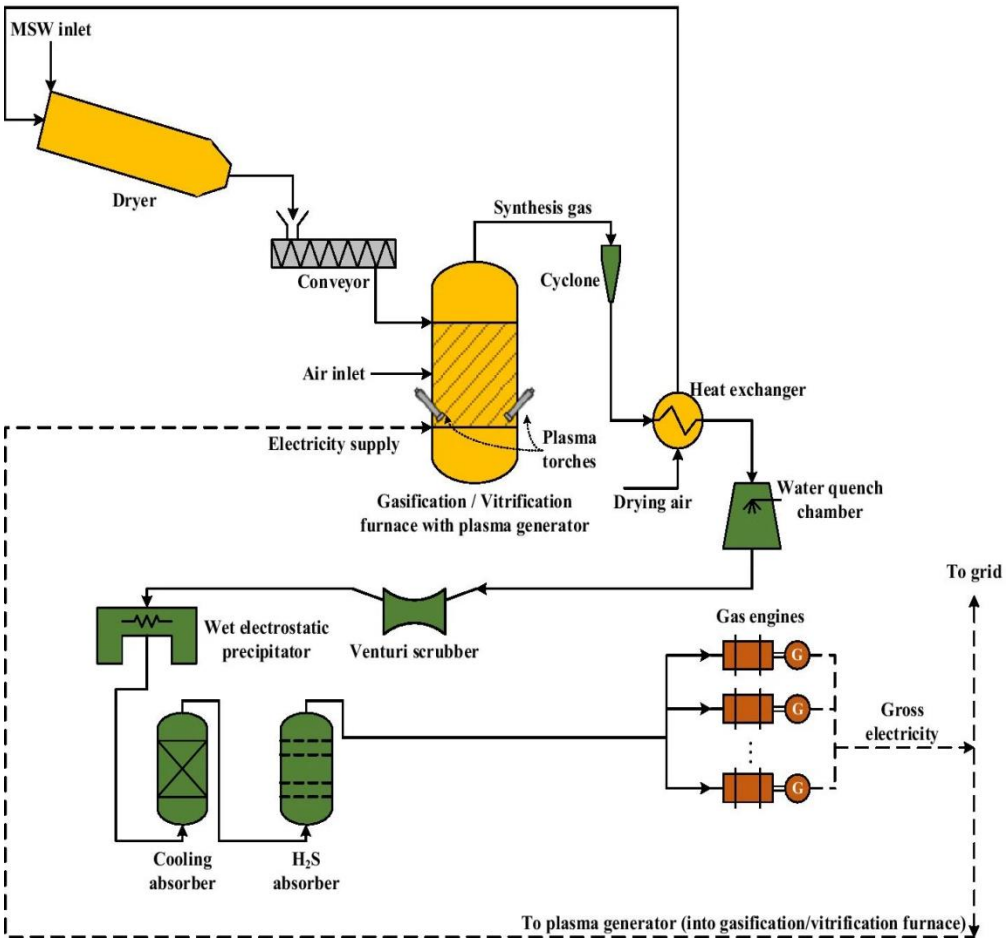


Figure 3: Schematic diagram of a plasma gasification process treating MSW [48].

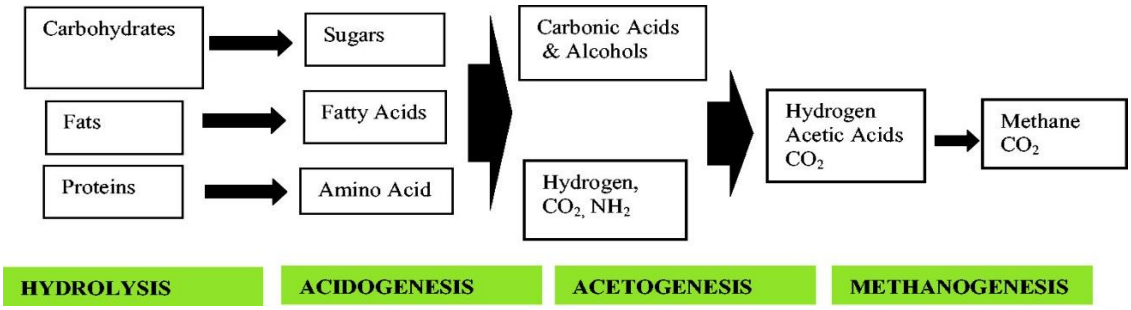


Figure 4: Phases of the anaerobic digestion process [57]

Thermal depolymerization

The thermal depolymerization (TDP) process converts various organic materials into crude oil-like products by applying high pressure and temperature in the presence of water. This method decomposes long-chain polymers into shorter monomers, simulating the natural geological processes that form fossil fuels. The first step in this process involves crushing the raw materials, such as coal, into small pieces and mixing them with water. Following this, the water/raw material mix is heated at a steady temperature of about 250°C and pressurized. After the heating/pressurizing process, the resulting products can be classified into two categories: crude hydrocarbons and minerals, which are usually extracted through petroleum fractionation (distillation) [33].

Anaerobic Digestion

Anaerobic digestion (AD), or biomethanation, is a microbial process in which organic waste is converted to biogas under oxygen-free conditions [21,55,57]. The process can be broadly divided into two stages (Fig. 4), which shows the breakdown of complex organics into simple acids by acidogenic microbes, followed by their conversion into methane by methanogenic archaea [31-33]. More specifically, AD involves four successive steps: hydrolysis, where enzymes degrade macromolecules into soluble compounds; acidogenesis, in which these products are fermented into volatile fatty acids; acetogenesis, which converts these acids into acetic acid and other intermediates;

and methanogenesis, where archaea generate methane as the principal output [33].

The biogas generated from this process is composed mainly of methane (CH_4) and CO_2, together with traces of sulfide and ammonia. Biogas can be used to produce heat and electricity utilizing combustion engines, microturbines, and combined heat and power plants [51]. Table 3 presents the main EfW technologies analyzed together with their respective advantages and disadvantages from USW.

Table 3: Waste-from-Energy technologies [2, 30, 31, 33, 35]

Technology	Advantages	Disadvantages
Incineration	- Achieves up to 90% reduction in the volume of municipal solid waste, thereby decreasing landfill demand. - Capable of continuous operation with high-capacity units. - Most effective for waste with high calorific value. - Enables energy recovery through electricity generation or combined heat and power (CHP) systems.	- Residual ash often contains elevated levels of heavy metals. - Releases hazardous compounds such as SO_x, NO_x, dioxins, and hydrogen chloride. - Inefficient for moist, low-calorific, or chlorine-rich waste. - High investment and operational expenses.
Gasification	- Produces syngas or fuel oils that can be applied in diverse energy systems. - Reduces waste volume by approximately 90%. - Lowers environmental emissions compared to landfilling. - Applicable to multiple waste types.	- Tar generation can hinder efficiency. - High moisture content limits energy recovery. - More suitable for large-scale power generation plants using Rankine cycles.
Pyrolysis	- Yields high-quality fuels such as char, bio-oil, and syngas. - Appropriate for carbon-rich waste. - Achieves reductions in both volume and mass of MSW. - Produces relatively low NOx and SO_2 emissions.	- Risk of coke buildup from liquid fuels. - Pyrolysis oils often exhibit high viscosity. - Excessive waste moisture reduces process efficiency.
Plasma Arc Gasification	- Capable of processing virtually any type of waste, including hazardous streams. - Reduces landfill burden by up to 99% by vitrifying residues into stable slag. - Generates valuable syngas for electricity production via turbines or engines. - Produces comparatively fewer atmospheric emissions than other energy-from-waste (EfW) methods. - Considered one of the most advanced and efficient EfW options.	- Requires higher initial capital due to the use of plasma torches. - High electricity consumption for operation. - Among the most costly EfW technologies to implement.
Landfill Gas (LFG)	- Methane-rich gas (40–60%) can be recovered and used as fuel. - Suitable for generating power or direct thermal energy. - Does not require highly skilled operators. - Can provide heat for boilers.	- Emissions may cause odor problems. - Risk of fire and explosion near landfill sites. - Leachate can contaminate soil and groundwater. - Captures only about 30–40% of potential gas output. - High transport costs.
Thermal Depolymerization	- Stabilizes heavy metals by converting them into oxides. - Recovers energy from organic matter without pre-drying, separating liquid fuels from water efficiently. - Lower gasification temperatures minimize energy loss during gas cleaning and simplify handling. - Fuel gas produced is free of harmful alkali metals. - Can treat unconventional feedstocks (tar sands, shale, heavy residues).	- Requires additional refining since it only fragments polymers into smaller molecules rather than producing finished fuels. - At higher than 400 °C, may emit CO_2, CH_4, dioxins, and furans. - Technology remains economically limited for crude oil replacement.
Anaerobic Digestion	- Produces biogas with higher methane content and lower CO_2 compared to landfills. - Well-suited for organic-rich waste streams. - Digestate (liquid and solid fractions) is valuable as fertilizer. - Enclosed systems minimize odors, pests, and social opposition.	- Inefficient for waste with a low organic fraction. - Requires adequate segregation to improve efficiency. - Unsuitable if biodegradable matter is insufficient. - Poor management can result in odor nuisances.

Data and Methods

This research applied a hybrid approach combining grey system theory with the additive ratio assessment method to support sustainable waste-to-energy planning in Tunisia. The integration of multiple Multi-Criteria Decision-Making (MCDM) techniques enhances the robustness of the findings, while the use of grey numerals enables the management of uncertainties inherent to long-term planning. The selection and prioritization of criteria relevant to EfW implementation were guided by an extensive review of the existing literature and expert consultations (see Table 4).

Table 4: Criteria for prioritizing EfW technologies

Criteria	Denotation	Criteria attribute	References
Generated Energy	C_1	Benefit	[13, 16, 53]
Capacity	C_2	Benefit	[13, 16, 53]
Technical maturity	C_3	Benefit	[13, 16, 53]
Efficiency	C_4	Benefit	[54, 55]
Employment opportunity	C_5	Benefit	[16, 53]
Social Opposition	C_6	Cost	[16, 53]
GHG mitigation	C_7	Cost	[16, 53]
O&M Cost	C_8	Cost	[16, 53]
Investment Cost	C_9	Cost	[16, 53]
Land Cost	C_{10}	Cost	[54, 55]

Multi-Criteria Decision-Making provides structured tools for evaluating alternatives in situations with multiple, often conflicting, objectives. By assigning weights to criteria, these methods help balance trade-offs and support evidence-based decision-making in fields such as engineering, economics, and management [60–65]. Their strength lies in integrating qualitative and quantitative inputs to reconcile differing preferences, a feature that has proven valuable across disciplines, including information systems, computer science, and behavioral decision sciences [66, 67]. A variety of techniques, such as AHP, TOPSIS, SWARA, DEMATEL, fuzzy AHP, fuzzy TOPSIS, BWM, and DEA, illustrate the breadth of the field [70–75]. Although widely applied, MCDM continues to evolve as new approaches emerge to address evolving decision-making challenges.

3.1 The Grey System Theory

When decision-making involves incomplete or uncertain data, Grey System Theory provides a structured framework for modeling such ambiguity [76–78]. Developed by Deng in 1982, this approach is especially suited to complex systems with limited quantitative data, distinguishing between white systems (complete information), black systems (no information), and grey systems (partial information).

In this method, uncertain values are expressed as grey numbers, defined by an interval representing the possible range of values. Key parameters include:

- Core value, midpoint of the interval ($\otimes$),
- Degree of greyness, measure of uncertainty (g°),
- Degree of whitening, likelihood that the value lies near the midpoint.

Grey number theory has been applied across various fields, including energy planning, economics, and engineering, due to its adaptability to sparse datasets.

The Grey Additive Ratio Assessment

Turskis and Zavadskas developed the Grey Additive Ratio Assessment (ARAS-G), which uses multiple factors to rate alternatives and identify the best solution [77]. The ARAS approach consists of creating a decision matrix, normalizing and weighting it, computing the total and relative desirability of each option, and ranking the options. The utility function, which calculates the complex relative efficiency of an appropriate alternative, is proportional to the influence of criteria values and weights [78]. The ARAS method's main merits are its simplicity and speed, its versatility across various criterion types, and its clarity in presenting results to decision-makers. Turskis and Zavadskas [79] described the ARAS-G technique steps as follows:

1. Construct the initial gray matrix.

$$X_{ij} = \begin{bmatrix} \otimes x_{01} & \otimes x_{02} & \cdots & \otimes x_{0n} \\ \otimes x_{21} & \otimes x_{22} & \cdots & \otimes x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes x_{m1} & \otimes x_{m2} & \cdots & \otimes x_{mn} \end{bmatrix}, i = \overline{0,m}; j = \overline{1,n} \quad (1)$$

2. Compute the normalized matrix.

$$\otimes \overline{X}_{ij} = \begin{bmatrix} \otimes \overline{x}_{01} & \otimes \overline{x}_{02} & \cdots & \otimes \overline{x}_{0n} \\ \otimes \overline{x}_{21} & \otimes \overline{x}_{22} & \cdots & \otimes \overline{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes \overline{x}_{m1} & \otimes \overline{x}_{m2} & \cdots & \otimes \overline{x}_{mn} \end{bmatrix}, i = \overline{0,m}; j \quad (2)$$

With

$$\begin{cases} \otimes \overline{x_{ij}} = \dfrac{\oplus x_{ij}}{\sum_{i=0}^{m} \otimes x_{ij}}, & \textbf{\textit{Benefit criterion}} \\ \otimes x_{ij} = \dfrac{1}{x_{ij}^{*}} \otimes \overline{x_{ij}} = \dfrac{\oplus x_{ij}}{\sum_{i=0}^{m} \otimes x_{ij}}, & \textbf{\textit{Cost criterion}} \end{cases} \quad (3)$$

3. Calculate the weighted normalized matrix.

$$\otimes \hat{x}_{ij} = \otimes \overline{x}_{ij} \times \otimes w_j; i = \overline{0,m} \quad (4)$$

4. Calculate the optimal function's value.

$$\otimes S_i = \sum_{j=1}^{n} \otimes \hat{x}_{ij}; i = \overline{0,m} \quad (5)$$

5. Convert the gray numbers into crisp values.

$$S_i = \frac{1}{2}(S_{i\alpha} + S_{i\gamma}) \quad (6)$$

6. Calculate the utility value of each option.

$$K_i = \frac{S_i}{S_0}; i = i = \overline{0,m} \quad (7)$$

Results and discussion

The use of Grey System Theory enabled a more nuanced understanding of the importance of numerous assessment criteria in the economic and technical sectors (Tables 5–7).

In the economic assessment of energy-from-waste technologies, investment cost (C9) was the most relevant criterion, with a weight of 14.99% (Fig. 5). O&M costs followed closely, with a weight of 14.33%, reinforcing the significance of cost considerations in EfW project feasibility. From a technical standpoint, energy generation capacity proved paramount, receiving the third-highest weight of 13.67%. Overall, plant capacity is a key determinant of processing capability, followed by a score of 11.04%. The remaining criteria exhibited comparatively lower weights, ranging from 8.9% for greenhouse gas emissions to 6.75% for employment opportunities. This distribution of weights underscores the expert-derived prioritization of each criterion, providing a critical understanding of the key drivers shaping EfW technology selection judgments.

The growing global emphasis on sustainable waste management and renewable energy generation requires the development of appropriate waste-to-energy systems, particularly in rapidly expanding urban areas such as Greater Tunis. This study used a robust multi-criteria decision-making framework based on Grey System Theory and the ARAS-G approach to determine the best EfW systems for Tunisia. This selection procedure considered a variety of Tunisian-specific factors, including waste composition, resource availability, and socio-economic conditions. It resulted in a comparative ranking of seven significant EfW

Table 5: Linguistic ratings and their corresponding grey rating values

Criteria importance assessment			Criteria value assessment		
Very Low	VL	[0.0 – 0.1]	**Very Poor**	VP	[0.0 – 1.0]
Low	L	[0.1 – 0.3]	**Poor**	P	[1.0 – 3.0]
Medium Low	ML	[0.3 – 0.4]	**Medium Poor**	MP	[3.0 – 4.0]
Medium	M	[0.4 – 0.5]	**Fair**	F	[4.0 – 5.0]
Medium High	MH	[0.5 – 0.6]	**Medium Good**	MG	[5.0 – 6.0]
High	H	[0.6 – 0.9]	**Good**	G	[6.0 – 9.0]
Very High	VH	[0.9 – 1.0]	**Very Good**	VG	[9.0 – 10.0]

Table 6: Verbal evaluations and importance weighting of the ranking criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Exp1	VH	M	H	H	L	VH	VH	H	VH	M
Exp2	H	VH	H	M	M	L	H	VH	H	VH
Exp3	VH	H	VL	M	H	M	VL	H	VH	M
Exp4	H	H	M	M	M	M	H	VH	VH	VL
Exp5	H	M	M	VL	L	L	L	VH	VH	M
Avg	0.830	0.670	0.490	0.430	0.410	0.450	0.540	0.870	0.910	0.470
Normalized Wight	0.137	0.110	0.081	0.071	0.068	0.074	0.089	0.143	0.015	0.077

Table 7: The initial ARAS-G matrix

		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Incineration	A_1	VG	G	F	G	VG	VG	F	F	P	F
Gasification	A_2	P	F	F	F	G	F	P	F	P	G
Pyrolysis	A_3	F	F	G	F	G	P	G	VG	VG	G
Plasma arc gasification	A_4	P	P	F	F	G	P	F	F	G	G
Landfill gas	A_5	G	VG	P	G	VG	VG	G	G	P	P
Depolymerization	A_6	VP	G	F	G	F	P	F	VP	P	F
Anaerobic Digestion	A_7	F	G	VG	G	F	P	F	VG	G	G

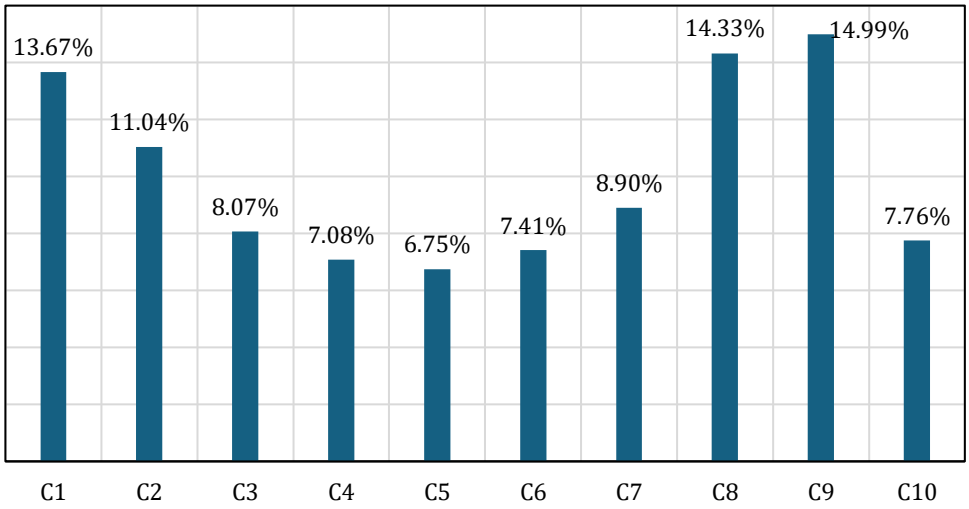


Figure 5: Grey weights of criteria

technologies using a complete set of preset criteria and sub-criteria. Moreover, the outcomes indicate that alternative A5 (landfill gas) is the preferred EfW application for Tunisia, followed by A7 (anaerobic digestion), as illustrated in Table 8. This prioritization is attributed to the relative simplicity and lower skill requirements of landfill gas projects, as well as lower capital and operational costs compared with more technologically complex thermochemical conversion processes.

Paradoxically, despite these inherent advantages and the abundance of readily available feedstock in Tunisia's existing landfills, the country currently lacks operational gas-to-energy landfill plants. This illustrates a major opportunity to create institutional and regulatory bodies that can attract the investment required for projects in this area. Establishing

Table 8: ARAS-G Final Ranking using the ARAS G

Alternative	Si	Ki	Rank
A_0	0.253	1.000	-
A_1	0.133	0.520	3
A_2	0.117	0.465	4
A_3	0.115	0.454	5
A_4	0.083	0.329	7
A_5	0.142	0.561	1
A_6	0.109	0.431	6
A_7	0.134	0.532	2

national strategic development plans (including landfill gas plants) and effective, efficient waste collection methods will provide an essential basis for developing this technology in Tunisia.

Landfill gas has been identified as the top alternative to landfills in the MCDM evaluation; Anaerobic and Aerobic Digestion have also been recognized as good alternatives, as have rural communities that generate large amounts of agricultural waste. The Biologically based systems will provide a means for local power generation and decrease dependency on Centralized Power Grids. Additionally, the emphasis on Environmental Criteria in the MCDM Evaluation underscores the need for transparent pollution-prevention laws and for assessing the overall environmental impacts of all EFW Technologies.

Finally, increasing public awareness regarding the environmental and health implications of improper waste management can significantly enhance resident cooperation and participation in source-separated waste collection programs, which are crucial factors for the participation in source-separated waste collection programs, which are crucial factors for the participation in source in source-separated waste collection programs, which are crucial factors for the successful development and operation of landfill gas-to-energy plants.

Sensitivity analysis

While the results of the multi-criteria decision assessment clearly indicated that landfill gas recovery was the most preferred EfW technology in Tunisia, it should be recognized that these results depended on both the input data and subjective decision-maker judgments. As such, an extensive dynamic sensitivity analysis was performed to provide confidence in the robustness of the results and to determine whether changing the relative importance of one or more criteria may alter the ranking order of technologies or their performance under different future scenarios.

The Sensitivity Analysis was performed on four different cases: an equally weighted case that had equal weighting for every criterion (each at 10%), and three other cases that emphasized one of the three aspects: economic weighting (20%), technical weighting (20%), and socio-environmental weighting (20%). All the remaining criteria for each weighting case were then weighed proportionately to produce a total weighting value of 100%

The sensitivity analysis demonstrated that the ranking of the technologies varied significantly across scenarios. It also highlighted the need to consider various aspects of EFW. For example, landfill gas (A5) consistently ranked first when comparing with the current and in an economically focused scenario. However, it ranked sixth in the socio-environmental scenario (see Fig. 6), highlighting potential trade-offs between economic and social/environmental factors for EFW. Aerobic digestion (A7), on the other hand, is highly consistent in its high ranking across the technical, socio-environmental, and equal-weight scenarios. This demonstrates that aerobic digestion may be a more robust and flexible EFW option than others, and that changes in the priorities of criteria are less likely to affect its ranking. On the contrary, plasma gasification (A4) consistently ranked last across most scenarios due to its poor performance relative to the other options studied under all evaluation criteria.

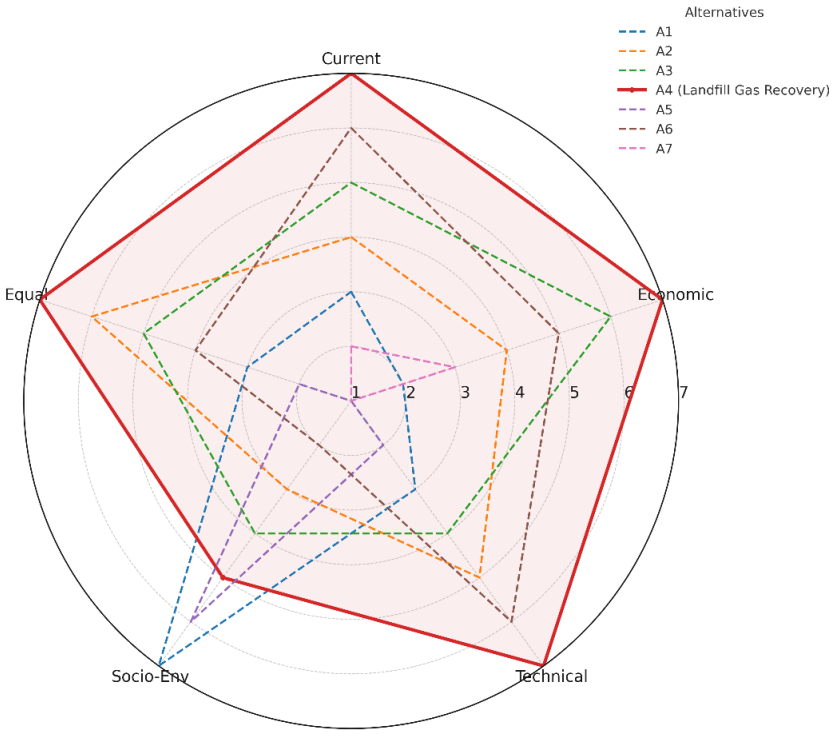


Figure 6: Sensitivity analysis concerning influential criteria.

Contextualizing the findings within previous research and sustainable energy planning

The transition toward sustainable waste management and resource-efficient energy systems requires integrated decision-support frameworks capable of reconciling competing technical, economic, environmental, and socio-institutional objectives. Recent advancements in multi-criteria decision-making (MCDM), geographical information

systems (GIS), mathematical optimization, and uncertainty-aware modeling have considerably strengthened the evaluation of alternative energy technologies. In Tunisia, Rekik and El Alimi [59,70–73,78,80–83] established several GIS-based and hybrid MCDM frameworks to identify suitable renewable energy investments by incorporating geographical constraints, infrastructure accessibility, resource availability, and economic considerations. These investigations were subsequently extended to sustainable wind infrastructure planning [84], spatial and techno-economic assessments of renewable hydrogen production [74,85,86], and comparative renewable electricity technology selection [96]. Complementary research by Richards et al. [64,65] demonstrated how GIS–MCDM can integrate environmental considerations, stakeholder preferences, and geographical suitability into solar and wind energy planning. Earlier investigations of Jamaica's renewable energy potential [113,117] and broader assessments of spatially distributed energy resources [120] further demonstrated the importance of location-dependent resource characteristics and development constraints. Collectively, these studies emphasize that technology selection should be treated as a multidimensional planning problem rather than an assessment based exclusively on energy generation potential.

The integration of technical reliability and uncertainty analysis into energy planning constitutes another important research direction. Salhi et al. [104,105] developed linear parameter-varying (LPV) representations of doubly fed induction generator-based wind energy conversion systems, investigating how uncertain operating parameters influence system modeling and stability. Subsequently, Salhi and Salhi [106,107] employed robust linear quadratic regulator (LQR) control and linear matrix inequality (LMI) formulations to improve active and reactive power tracking under variable operating conditions. Although these studies address wind energy conversion rather than waste treatment, they demonstrate a transferable methodological principle: the performance of energy technologies must be evaluated with explicit consideration of parameter uncertainty, operational variability, and system reliability. More recently, Rekik et al. [108] investigated advanced hybrid nanofluid heat-transfer characteristics, providing additional insights into thermal-performance modeling and energy-efficiency improvement. These developments are relevant at the broader engineering level because EfW facilities also depend on stable operating conditions, effective thermal-energy recovery, and reliable conversion performance, particularly when processing heterogeneous waste streams.

Studies focusing directly on waste valorization provide stronger evidence concerning the practical feasibility of energy recovery from organic and municipal waste. Richards and Yabar [21,28] demonstrated the potential of biogas production and agricultural waste utilization for decentralized electricity generation and resource recovery. Related investigations by Sharmin et al. [53] and Ogbonna et al. [56] further emphasized the importance of feedstock characteristics, thermal pretreatment, anaerobic conversion conditions, and methane productivity in determining bioenergy feasibility. Building upon these perspectives, Richards and Yabar [119] examined the accessibility of energy production from sugarcane bagasse and animal waste in Jamaica, while Richards et al. [118] extended the analysis through GIS-based suitability assessment of biogas facilities utilizing agricultural residues and livestock manure. These contributions demonstrate the importance of integrating feedstock availability, spatial accessibility, resource logistics, and potential electricity generation into waste-to-energy planning. Similarly, Kumar et al. [32] examined solar-assisted thermochemical conversion of agricultural residues into biofuels, highlighting opportunities to integrate renewable heat and advanced process optimization into biomass valorization. Taken together, these investigations suggest that the relative suitability of an EfW technology depends not only on its conversion mechanism but also on feedstock characteristics, preprocessing requirements, supply-chain organization, and operational compatibility with local conditions.

Environmental performance and circular resource recovery represent equally important dimensions of sustainable technology selection. Matagi et al. [31] integrated life-cycle assessment (LCA), GIS, and waste-treatment strategies to investigate solid waste management alternatives in Fiji, illustrating how geographical conditions and environmental consequences can inform infrastructure planning. Esopere et al. [109] combined life-cycle assessment with system dynamics modeling to evaluate household electronic-waste management in Cameroon, demonstrating the importance of assessing treatment pathways within a broader system of waste generation, resource recovery, and environmental impacts. Complementary research by Tran et al. [110] investigated integrated electrochemical oxidation and filtration for industrial wastewater treatment, while subsequent work [111] examined biological thin films for heavy-metal biosorption. More recent investigations [116,121] explored the conversion of industrial aluminum by-products into hydrogen and potential water-treatment resources, although these preliminary findings require further peer-reviewed validation. These studies collectively illustrate the growing relevance of waste minimization, pollutant control, and value-added resource recovery within circular economy strategies. From an EfW perspective, such considerations are particularly important because energy generation alone does not necessarily imply environmental superiority; residual emissions, secondary pollutants, material recovery, and downstream treatment requirements must also be incorporated into comparative assessments.

An integrated energy–environmental perspective is further supported by research on alternative low-carbon conversion pathways. Guzman-Urbina et al. [115] investigated e-methanol production through direct air capture, carbon dioxide hydrogenation, and hydrothermal co-electrolysis, demonstrating how process integration and energy recovery can influence lifecycle carbon performance. Likewise, broader investigations of hydrogen-based energy pathways [97], carbon-intensive industrial processes [95], and renewable electricity expansion [91–93,98,99] highlight the importance of evaluating technologies within their regional energy and emissions context. Richards et al. [22] also examined the challenges of renewable electricity transitions, while Ogbonna et al. [114] identified structural and operational constraints affecting power generation in Nigeria. Although these studies address different technologies and geographical settings, they reinforce the importance of infrastructure availability, economic feasibility, institutional capacity, and appropriate system boundaries in sustainability assessments.

The implementation of energy infrastructure is additionally exposed to risks that extend beyond conventional techno-

economic indicators. Shetwan et al. [75,87] employed structured risk-analysis methodologies to prioritize operational, financial, and institutional risks, demonstrating how uncertain external conditions can affect engineering project implementation. Similarly, Phyo et al. [112] combined hydraulic simulation and GIS-based flood-inundation mapping to inform infrastructure risk management. The methodological implications of these studies are relevant to EfW facilities, which may be affected by environmental hazards, disruptions in waste collection, financing constraints, and operational uncertainties. In parallel, emerging applications of machine learning to energy-system forecasting [89] and deep learning to infrastructure site selection [88] illustrate potential future avenues for improving the predictive capabilities of decision-support frameworks. The comparative assessment by Rekik et al. [100] further demonstrates the central role of structured MCDM approaches in reconciling competing sustainability objectives and supporting transparent energy planning.

Despite these advances, an important methodological challenge remains in translating general energy-planning approaches into practical waste-to-energy technology selection under incomplete and uncertain information. Unlike conventional renewable energy systems, EfW facilities must accommodate considerable variability in municipal waste composition, calorific value, moisture content, collection practices, and treatment requirements. Furthermore, technological maturity, capital investment, operation and maintenance costs, greenhouse gas emissions, land requirements, and social acceptance can influence technology suitability in conflicting directions. These challenges are particularly significant in developing countries, where limited availability of reliable project-level data and constrained institutional resources complicate the evaluation of alternatives. Consequently, deterministic assessments based on fixed criterion values may fail to adequately represent uncertainty in technical performance and expert preferences.

Against this background, the present study employs an integrated Grey System Theory–Additive Ratio Assessment (ARAS-G) framework to evaluate seven EfW technologies in Tunisia using ten technical, economic, environmental, and social criteria. Grey numbers provide a structured representation of incomplete or uncertain expert assessments, while ARAS-G enables systematic aggregation of weighted criterion values and comparison of alternative technologies. The assessment is complemented by scenario-based sensitivity analysis to examine the dependence of technology rankings on criterion weighting. The results identify landfill gas recovery and anaerobic digestion as the two highest-ranked alternatives under the baseline assumptions, although the ranking of landfill gas recovery changes substantially under increased socio-environmental weighting. This distinction is critical: the preferred alternative under current economic priorities is not necessarily the most resilient option across contrasting sustainability objectives. Accordingly, the proposed framework contributes a context-sensitive basis for identifying feasible EfW development pathways in Tunisia while recognizing the need for site-specific validation, lifecycle environmental assessment, and broader stakeholder involvement before investment decisions are finalized.

Recommendations and Directions for Future Research

This study shows significant potential and challenges in integrating energy-from-waste into Tunisia's evolving waste management system. MCDM techniques like Advanced Multi-Criteria Analysis (ARAS-G) have helped identify landfill gas collection and anaerobic digestion as the two top-priority energy-from-waste technologies available to Tunisia; however, several practical and institutional barriers continue to limit their implementation. To facilitate the translation of analysis into actual implementation, the authors propose several avenues for future investigation and offer recommendations.

Policy and Regulatory Recommendations

To drive successful EfW adoption in Tunisia, robust policy recommendations focus on creating enabling regulatory frameworks, introducing targeted economic incentives, and prioritizing public awareness and participation. These actions collectively strengthen governance, reduce investment barriers, and foster greater societal acceptance and involvement in EfW initiatives.

- Foster enabling frameworks: The development of robust regulatory and institutional frameworks is essential. Tunisia should establish clear policies and streamlined permitting processes for EfW projects, with explicit targets integrated into national waste and energy strategies. Coordinated governance between local, regional, and national authorities can minimize bureaucratic delays and ensure alignment with broader sustainability goals.
- Economic incentives: Policymakers should introduce targeted financial incentives, such as feed-in tariffs for renewable electricity from biogas, tax reductions on EfW investments, and grants for innovation in waste processing. These mechanisms can help offset high upfront capital costs and encourage private sector and international investor participation.
- Public awareness and participation: Given societal concerns, especially regarding technologies such as incineration, national campaigns are encouraged to raise awareness about the environmental and public health benefits of EfW solutions. Community engagement in the planning and operation of EfW plants can also increase acceptance and encourage source separation of waste, thereby enhancing the quality of feedstock for biological conversion technologies.

Technical and Operational Recommendations

The need for an adequate feedstock supply to support the reliable and efficient operation of EfW plants depends on investments in waste stream optimization. Therefore, it is necessary to invest in upgrading and increasing capacity within the waste collection network, upgrading current municipal practices for separating waste at source, and creating efficient networks for the collection of both organic and residual waste streams, which are critical for anaerobic digestion and landfill gas recovery.

Simultaneously, capacity building must also take a high priority through targeted training for technicians, plant operators, and municipal officials to address issues related to EfW system design, operational efficiency, maintenance, and best practices. These efforts may be enhanced by international organizations that provide mechanisms to facilitate technology transfer and bridge local technical knowledge gaps. In parallel, ongoing life-cycle and environmental assessments should occur at all EfW facilities to provide data on emissions and assess material recovery (resource recovery) at each facility, enabling assessment of the true sustainability outcomes of these projects.

Future Research Directions

Future research in Tunisia should focus on conducting full-scale feasibility studies. This would help address the current problem of relying mostly on literature-based and expert-derived data. It would also allow for better technological choices and where to deploy them. Furthermore, additional empirical research is needed to understand better how Tunisians view different types of EfW technologies. By using both qualitative and quantitative research methods, it can be determined what works best to communicate effectively with the local communities and encourage public participation during the planning phase.

Moreover, integrating EfW into the broader context of circular economic initiatives must be studied to maximize economic, environmental, and social benefits. In addition, further study of new methods to structure business models and financial structures that enable public-private partnerships, blended finance schemes, and carbon credit programs is crucial. Therefore, such developments would provide Tunisia with greater adaptation options, increasing the overall sustainability and feasibility of EfW projects in the future.

Conclusion

The objective of this research was to determine which EfW technology is best suited to Tunisia using a robust MCDM methodology that combines ARAS and Grey System Theory. The authors evaluated the suitability of seven Energy-from-Waste technologies (landfill gas recovery, anaerobic digestion, incineration, gasification, pyrolysis, depolymerization, and plasma gasification). They applied about 10 key criteria (energy generation, capacity, technical maturity, efficiency, costs, etc.) to each evaluated option.

The evaluation showed that landfill gas was identified as the top technology based on an overall ranking (Ki) of 0.561; second was anaerobic digestion (Ki = 0.532); and third was incineration (Ki = 0.520), although it is well-established as technically and economically viable, largely because of environmental pollution concerns. Plasma gasification consistently ranked last (Ki = 0.329) in terms of investment costs and efficiency. Based on the assigned weights, investment cost had the largest impact on decision-making, with a weighting of 14.99%; operation and maintenance cost was second at 14.33%; and energy generation capacity was third at 13.67%.

The results of the sensitivity analysis showed significant variations in the rankings of the alternatives under different weightings. The ranking of landfill gas changed significantly (from 1st to 6th) when socio-environmental weights were used instead of economic ones. These findings show how important it is to develop a specific technology selection strategy that can be adapted to local contexts to improve governance mechanisms, provide financial incentives, and facilitate public participation, thereby supporting waste-to-energy development in Tunisia, addressing waste management problems, and advancing renewable energy strategies effectively.

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