Renewable and Sustainable Energy Reviews 207 (2025) 114818

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Prioritizing industrial wastes and technologies for bioenergy production: Case study

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ARTICLE INFO

Keywords:
Waste management
Bioenergy
Pollution control
Multi-criteria decision-making (MCDM)
Environmental impact

ABSTRACT

Energy supply stability in the industrial sector is crucial to maintain operational efficiency and avoiding costly disruptions. In the face of pressing environmental challenges, transitioning to sustainable, efficient, and eco-friendly energy sources is imperative. This study aims to assess the potential of industrial waste for bioenergy production in Khorasan Province, Iran, addressing the research gap of developing a comprehensive framework of criteria that was lacking in previous studies. Employing a combined technology and material assessment methodology, the research began with the collection and analysis of questionnaires to identify and weight critical criteria using Shannon Entropy and expert insights. The Additive Ratio Assessment method was then used to rank various types of industrial waste and technologies according to established value criteria. The Findings reveal that anaerobic digestion of organic waste emerges as the most viable bioenergy solution with an 85 % desirability score, followed by anaerobic digestion of sewage sludge and gasification of plastic waste, scoring 77.31 % and 69.41 %, respectively. The innovative aspect of this study is the development and implementation of five novel evaluation criteria, including process temperature, technology lifetime, production cost, waste collection cost, and waste separation cost, which have not been previously applied to the assessment of industrial waste for renewable energy production, especially in developing countries.

1. Introduction

After World War II, global industrialization led to significant growth in production of goods and services. This progress in high-volume production resulted in excessive pollution, posing serious environmental challenges [1]. The combustion of fossil fuels in industrial zones is a major air pollution source, threatening human health through the emission of harmful gases such as acid vapors and greenhouse gases.

There are different types of environmental pollution caused by industrial activities, endangering the health and lives of humans and animals. Industrial activities are a major source of air pollution, emitting harmful gases such as sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (PM). These pollutants can cause respiratory issues, cardiovascular diseases, and other serious health problems. Additionally, greenhouse gases like CO_2 contribute to climate change [2]. Industrial wastewater, often containing heavy metals, organic toxins, and other hazardous substances, poses significant risks to aquatic ecosystems and human health. Contaminated water can lead to diseases such as cholera, dysentery, and other gastrointestinal disorders. The improper disposal of industrial effluents is a leading cause of water pollution [3]. Hazardous waste from industries, including chemicals and heavy metals, can lead to soil contamination. This not only affects soil fertility and agricultural productivity but also poses health risks through the food chain, potentially causing cancers and other health issues [4]. The accumulation of industrial solid waste, particularly plastics and other non-biodegradable materials, contributes significantly to environmental degradation. These wastes can persist in the environment for centuries, harming wildlife and ecosystems. The production of renewable energy from these wastes is an effective way to mitigate their environmental impact [5].

Nevertheless, industrial wastes hold significant potential for generating green energy, restoring environments, and conserving natural resources due to their organic and recyclable properties [6]. A substantial

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https://doi.org/10.1016/j.rser.2024.114818
Received 26 April 2024; Received in revised form 27 July 2024; Accepted 6 August 2024
1364-0321/

Nomenclature

General terms

ARAS Additive Ratio Assessment
MCDM Multi-Criteria Decision Making

Shannon Entropy Method

E_j the entropy of j-th criterion
k a positive constant coefficient and is between 0 and 1
r_{ij} Value of alternative i according to criterion j
P_{ij} the unscaled value of alternative i for criterion j
d_j Degree of deviation of criterion j
w_j the weight of criterion j
γ_j Arithmetic mean of experts' opinion about the importance of criterion j
w_j' the adjusted weight of j-th criterion

ARAS method

DMM Decision matrix
x_{ij} the value of the i-th alternative concerning the j-th criterion
$\overline{x}_{ij}$ the normalized value of alternative i in criterion j
$\widehat{x}_{ij}$ Weighted normalized value of alternative i for criterion j
S_i Optimization function for alternative i
K_i Relative effectiveness of alternative i

portion of water needed for irrigation can be sourced from treated industrial wastewater and sewage. Solid waste can produce a considerable volume of high-purity methane gas [7], while the by-products of decomposition serve as plant fertilizers. Separated metal scraps can be melted and repurposed across various industries. Similarly, plastics can be converted into energy, with leftovers recycled for new plastic production. Paper and cardboard recycling facilitates the creation of cellulosic products, conserving wood resources and natural habitats. Leveraging industrial wastes for green energy addresses environmental pollution, conserves fossil resources, and meets the energy demands of industrial sectors. Common industrial wastes pivotal for green energy in the industry sector are commonly categorized as organic waste, wood waste, paper and cardboard, and plastics.

Organic waste constitutes a significant portion of solid waste, including agricultural residues and food production sector by-products. These wastes vary significantly in size, structure, composition, and characteristics. Due to their simple structure, sugars within the organic waste are readily transformed into biofuels like ethanol, methanol, and hydrogen. The average energy value of organic waste is approximately 16,750 kJ/kg [8].

Wood wastes are an excellent source for producing solid, liquid, and gas fuels [9,10]. Annually, around 4 billion cubic meters of wood waste are utilized globally, with approximately 55 % directly burned to generate heat and electricity. In industrial nations, a significant portion of wood waste is employed to produce heat, steam, and electricity for factories, presenting a sustainable alternative to non-renewable fossil fuels. The International Energy Agency (IEA) reports that enhanced energy production technologies can yield 165 GJ of energy annually from each hectare of wood [11]. According to Table 1, the energy value of wood waste varies with moisture content: dry wood has a potential of 17.46 GJ per ton, whereas wood at 55 % moisture content offers 7.21 GJ per ton.

Paper and cardboard, derived from materials like wood pulp, cotton, and agricultural waste [13], are essential in industries, mainly as packaging and office waste. Despite their recyclability, only about a third is repurposed into newsprint, sanitary paper, and graph paper, with the rest used for energy generation through burning. On average, about 49 % of newspapers, 67 % of sanitary paper and tissue paper, 86 % of thin paper, and 52 % of cardboard boxes include their waste. According to Ref. [14], each kilogram of paper and cardboard can produce approximately 15,000 and 16,360 kJ/kg of energy, respectively.

Table 1
Potential of wood waste in electricity and thermal energy production [12].

	Piece of wood	Wood chips 25 %	Wood chips 30 %	Wood chips 45 %	Wood chips 55 %
Energy value (GJ/ton)	17.46 GJ	13.64 GJ	12.57 GJ	9.35 GJ	7.21 GJ
Energy value (MWh/ton)	4.85 MWh	3.79 MWh	3.49 MWh	2.59 MWh	2 MWh

Plastics are favored in products manufacturing due to their durability, lightweight, cost-effectiveness, flexibility, and resistance to corrosion and erosion. However, their widespread use across industries and inadequate waste management result in persistent, non-degradable industrial plastic waste. Common recycling methods include burning, chemical recycling, and burying [15], yet only 15–20 % of plastics undergo recycling through separation and shredding [16]. Consequently, energy recovery techniques like gasification, pyrolysis, and plasma treatment have gained prominence for converting plastic waste into energy [17]. According to available documents, each kilogram of plastic waste can yield 45,000 kJ/kg of energy [14].

In production processes, water is essential. Wastewater originates from activities such as cooling, heating, material processing, chemical reactions, and quality control [18]. Its quantity, pollution level, and flow intensity vary by industry, often containing toxic and organic substances. Industries like cement, pharmaceuticals, food production, rubber, textiles, paper, and organic fertilizers generate the most polluting wastewater [19,20].

Textile industry waste stems from processes like washing, drying, weaving, dyeing, printing, and production [21]. This industry significantly contributes to both air and water pollution. According to Ref. [22], fabric production releases 25 kg of CO_2 per kg of fabric and 16.9 kg of CO_2 for a mix of 50 % cotton and 50 % polyester. The energy value of one kg of fabric is around 17,000 kJ [14].

Leather production results in significant waste, including skin and fat residues, and wastewater [23]. From every 1000 kg of raw sheep and cow leather, only 255 kg are transformed into final products, leaving 745 kg as waste [24]. Traditionally, this waste is disposed of in landfills. However, given hazards associated with landfill, a more sustainable management approach is to convert leather waste into biogas [25], which typically comprises 55–70 % methane and 30–45 % carbon dioxide, along with side gases. According to Ref. [14], the energy value of leather waste is approximately 23,000 kJ per kg.

Oils produced from different industries are mixed during the stages of collection, storage, and transportation and create a mixed oil called oily waste [26], which leads to significant environmental contamination. Annually, around 24 million tons of this hazardous waste are generated [27]. Despite its potential for pollution, converting oily waste into biofuels for turbines and engines offers environmental and energy-saving benefits. Pyrolysis, in particular, is effective in turning various industrial oil wastes into biofuels, with each kilogram holding an average energy value of 42,400 kJ [28].

In recent decades, numerous studies have been conducted on utilizing industrial waste for energy. However, comprehensive research that jointly evaluates technology and waste for green energy production from industrial wastes is particularly lacking in developing countries, such as Iran. This study aims to bridge this gap by providing a holistic assessment of common industrial wastes for green energy generation, integrating multiple dimensions of variability to surpass the limitations of one-dimensional analyses.

The novelty of the current study lies in establishing five new evaluation criteria: process temperature, technology lifetime, production cost, waste collection cost, and waste separation cost. These criteria are critical in assessing the energy generation potential, particularly in developing countries, but have not been previously considered in the context of assessing industrial waste for renewable energy generation.

Most studies on industrial waste utilization for energy focus on the type and composition of waste, but they often overlook the critical role of process temperature in determining the efficiency and feasibility of different energy conversion technologies. For example, a study by Salem et al. [29] analyzed various energy conversion technologies but did not consider the specific impact of process temperature on the overall efficiency and economic viability. The longevity of the technology used for waste-to-energy conversion is crucial for economic and environmental sustainability. The research by Nubi et al. [30] discusses various waste to energy technologies and evaluates their environmental impacts. However, it does not delve deeply into the longevity of these technologies, which is crucial for understanding long-term benefits and maintenance costs.

While many studies, such as those by Wu et al. [31], discuss various aspects of bioenergy production, including environmental impacts and the potential of bioenergy crops, they often do not provide a detailed analysis of the costs associated with production, such as initial investment, operational costs, and scalability. A review by Kharmawphlang et al. [32] discusses various waste-to-energy technologies, emphasizing their environmental benefits and potential for energy recovery. However, it does not provide a detailed analysis of the logistics and costs associated with waste collection, which are crucial for assessing the feasibility of waste-to-energy projects.

Effective waste separation is crucial for maximizing energy recovery from industrial waste. Studies like those by Shah et al. [33] emphasize the importance of waste separation in the context of energy recovery, highlighting the environmental benefits and efficiency improvements achievable through proper waste segregation. However, these studies often do not address the costs associated with these processes, such as initial investments and operational expenses. This study fills that gap by providing a detailed cost analysis using the MCDM (Multi-Criteria Decision-Making) methodology, ensuring a more comprehensive evaluation. By incorporating five novel criteria, this study offers a holistic and practical framework for assessing the potential of industrial waste for renewable energy generation. This comprehensive approach addresses critical gaps identified in previous studies, making significant contributions to the field, particularly in developing countries where such detailed analyses are often lacking.

The remainder of the research is organized as follows: Section 2 presents a literature review to identify gaps in existing relevant works. Section 3 provides methodological details and outlines the research process. Section 4 analyzes the results of the MCDM methods and quantitative modeling. Finally, Section 5 offers a concise conclusion summarizing the study's key findings and highlights the most significant results.

2. Literature review

The literature reveals an increasing interest in converting industrial wastes into renewable energy, particularly through methods such as pyrolysis, gasification, and anaerobic digestion [34]. These techniques have proven effective in transforming waste from diverse sectors, including agriculture, textiles, and chemicals, into valuable energy resources. In the following, a literature review and a summary of previous research in this context are presented.

Caputo et al. [35] investigated the economic and technical aspects of heat recovery in the olive oil production industry. They tested a combination of wastewater from olive oil production, olive peel, and washing wastewater. The economic analysis considered various indicators, including investment costs, repair costs, energy product revenues, and waste disposal costs. The economic performance analysis encompassed wastewater disposal cost reduction, income from energy production, net present value, and profitability index. The research results indicate that this method of energy recovery in the power plant yields high profitability. Lunghi & Burzacca [36] conducted a study on converting confectionery industry waste into biogas. They measured various indicators such as waste flow, chemical composition, waste size, and heating value. The investigated wastes encompassed fruit and vegetable waste, paper waste, packaging waste, and other production by-products. Analyzed indicators included the performance of absorption machines, electric compressors' efficiency, boiler efficiency, the amount of heat energy recycled, electrical energy reduction, the power available from coolers, and cost savings. The analysis and tests indicated that the introduction of a fuel cell system has led to an increase in energy production.

Shuit et al. [37] conducted a study on the economic feasibility of producing industrial and synthetic biofuels and generating electricity from palm oil waste in Malaysia. They investigated issues related to the availability and sustainability of raw materials, as well as the current utilization of palm oil biomass. The biomass examined in this research included fruit brunches, fiber, shell, fronds and trunks, and palm kernel. The research results indicated that Malaysia has significant potential to convert palm waste into energy, potentially supplying a considerable portion of the country's energy demand. Stillwell et al. [38] studied energy recovery in wastewater treatment plants using the anaerobic digestion method to use biogas and the combustion of biosolids to produce electricity in the United States. The important items examined in this research include the quantity of electricity used, the amount of energy recovery, net consumption, net electricity consumption of each unit, and the amount of biogas. According to their findings, using anaerobic digestion and biogas can reduce electricity consumption between 2.6 % and 27 % and cause up to 83 % reduction in electricity consumption in Texas, as well.

Marculescu & Stan [39] conducted experimental research on utilizing poultry industry waste for energy production. They proposed processes based on the physical, chemical, and thermal properties of the waste to generate energy, as opposed to direct combustion. The focus was on chicken feathers, a significant byproduct of poultry farms. Their findings indicate that water content significantly affects the efficiency of the pyrolysis process in converting poultry waste into energy. Consequently, as the drying process reduces the waste's moisture content, the efficiency of the conversion process improves, resulting in increased energy output. Zhang et al. [40] introduced a new techno-economic model for energy recovery from industrial waste in the iron and steel industry. They evaluated the technological and economic characteristics of waste recycling technologies and energy sources. Various forms of energy, including chemical, thermal, and pressure energy, were assessed. Their results indicate that energy price and discount rate are the most sensitive and crucial factors for cost efficiency. Furthermore, the application of this technology enables the recovery of approximately 44 % of wasted heat energy.

Delpech et al. [41] explored the use of heat pipes as heat exchangers in ceramic industry processes to enhance energy efficiency. The study analyzed heat recovery from the cooling chimney of furnaces utilizing heat pipe technology. A theoretical model was developed for this purpose, and numerical simulations were conducted based on the technological characteristics and actual performance of ceramic processes. The results demonstrate that this technology can recover more than 863 MWh of energy annually, which can be utilized to heat the preheating process of dryers. Additionally, it leads to a reduction of 164 tons of carbon dioxide emissions and lowers energy costs by 22,120 euros per year. Khalil et al. [42] assessed the potential for biogas production from animal and poultry wastes in Indonesia. They introduced waste-to-energy conversion technologies to estimate the capability of transforming livestock waste into biogas. Livestock and poultry wastes were examined, with indicators for modeling and potential measurement, including waste type, reactor design and mapping, pH, temperature, and available waste volume. The results show that using various animal wastes, including manure and blood, can produce approximately 9597.4 million m^3 of biogas annually. This produced biogas could then be converted into about seventeen billion kWh of electricity per year. The conversion of biogas into electricity involves several steps to ensure efficiency. Firstly, biogas is produced through anaerobic digestion. It is then purified to remove impurities like hydrogen sulfide and moisture. The purified biogas fuels biogas-powered generators or combined heat and power (CHP) systems. In these systems, biogas is used in an internal combustion engine to drive a generator that produces electricity. The process also generates heat as a byproduct, which can be utilized for heating purposes, improving the overall efficiency of the system.

Arita et al. [43] explored the optimization of biodiesel production using the innovative catalyst DES K2CO3-Glycerol. They employed the Taguchi method, specifically a 16-run orthogonal array (L16) with two levels and four factors, to identify the most critical parameters for producing biodiesel from refined bleach-deodorized palm oil (RBDPO). The study used signal-to-noise ratio (SNR) and ANOVA analyses to evaluate the catalyst's efficacy, which proved to be the key factor affecting the quality of the biodiesel. Their results demonstrated that the optimal conditions for biodiesel production are 95 °C for 4 h with a catalyst concentration of four wt%, under which the biodiesel produced complies with international standards. Durmanov et al. [44] conducted a study to explore the impact of varying pyrolysis temperatures and durations on biochar properties. Their method involved a sequence of controlled pyrolysis experiments designed to systematically modify characteristics such as surface area, porosity, and chemical composition of biochar. The research revealed that increased temperatures and extended pyrolysis periods improve the carbon sequestration potential of biochar and its ability to enhance soil fertility, thus aiding climate change mitigation. The findings offer valuable insights into optimizing biochar production for environmental advantages.

Numerous studies have explored and ranked renewable energy sources, yet comprehensive research on technology-material prioritization for converting common industrial wastes into green energy remains lacking. Also, existing studies primarily focus on technical criteria, often due to governmental regulations emphasizing environmental considerations. However, there remains a gap for lacking a comprehensive framework that simultaneously evaluates different criteria for industrial waste utilization in bioenergy production. In this study, five new criteria, including process temperature, technology lifetime, production cost, waste collection cost, and waste separation cost, are introduced (Table 2). By incorporating economic and technical factors previously overlooked, this study aims to fill the existing gap and create a more comprehensive framework for assessment, leading to more accurate results. Given the considerable expense associated with technologies for converting industrial waste to energy, the precision and applicability of our findings hold paramount importance. The precision and accuracy of results should be compelling and have a significant influence on the decisions of managers and practitioners; and shows the necessity of a holistic criteria framework in this field.

The economic criteria considered in this study include technology investment cost, operation and maintenance cost, waste collection cost, waste separation cost, and production cost. In Iran, the easy access to and low cost of energy result in limited interest among industrial managers in adopting renewable energy [45]. Thus, the evaluation of economic criteria aims to motivate their shift towards renewable sources. Among the technical criteria, technology maturity, energy efficiency, technology lifetime, and process temperature are considered; this is crucial as sanctions against Iran limit access to advanced technologies available in industrialized countries, leading to the use of outdated or immature systems. Therefore, assessing technology's maturity and lifetime is essential. In the environmental category, the sole criterion is air pollution, which serves as a significant and cautionary factor. Given the easy access of Iranian industrial facilities to fossil fuels, there is a prevalent reliance on coal, gas, or oil, often overlooking the adverse atmospheric effects. Highlighting the environmental impact may encourage these entities to reconsider their energy sources and mitigate harmful practices.

3. Methodology

The scope of this research encompasses one thousand and ten factories within the Toos Industrial Zone in Mashhad, Iran, organized by the Organization of Industry, Trade, and Industry, and these factories are categorized into various industrial groups, including cosmetics and health, electrical and electronic, plastics, wood, pharmaceuticals, cellulose, chemicals, food, metals, yarn and fabrics, machinery and equipment, among others. All these factories generate wastes and residues that have the potential to be converted into bioenergy. The selection of the Toos Industrial Zone in Mashhad for this study was based on its significant industrial diversity, strategic importance, environmental impact, and the availability of comprehensive data and research support. These factors collectively make it an ideal location for assessing the potential of industrial waste for renewable energy generation.

The expert team for this research consists of twenty-five groups of professionals in waste management, energy management, and environmental sciences. These experts are employed within the Toos Industrial Zone, the Iranian Department of Environment, the Municipal Waste Management Department, and the Iran Energy Association. Each team member has a minimum of five years of relevant experience and holds educational qualifications ranging from bachelor's to doctoral degrees.

The research steps are as follows.

1) Identification of criteria and research alternatives:
   - Determining alternatives through direct visits to two hundred thirty factories over six months.
   - Identifying criteria through a literature review, including books, reports, research, and conferences.
   - Filtering criteria based on experts' opinions.
2) Data collection for each criterion:
   - Utilizing reports, research, and books.
3) Weighting the criteria:
   - Applying an integrated method of Shannon entropy and experts' opinions.
4) Application of the MCDM method (ARAS technique) for technology-material prioritization.

To identify research alternatives (industrial wastes), visits to a representative sample of two hundred thirty factories of various sizes were conducted, resulting in the identification of fifteen different types of industrial waste. From this list, eight types of waste commonly found across almost all industries were selected as the alternatives for this study. The findings of Koolivand et al. [55] support the results obtained in this phase.

A thorough literature review was conducted to develop a comprehensive set of plausible criteria. Subsequently, a preliminary list of criteria was compiled, and a questionnaire featuring forty-five criteria was distributed to experts, requesting their approval or disapproval of each criterion's relevance to this study. Criteria that garnered at least fifty-one percent approval from experts were deemed effective and retained for final ranking. Based on the questionnaire results, only eleven criteria met this threshold of acceptance and were thus selected as the research criteria. The use of a questionnaire to gather expert opinions on the degree of importance of each criterion allows for a systematic and democratic process of selection. This method ensures that the criteria chosen are validated by professionals with relevant expertise, thus enhancing the credibility and reliability of the research. Moreover, experts provide practical insights and industry-specific

Table 2a
Comparative analysis of prior research on industrial waste for renewable energy [46–54]

Author (s)	Aim of research	Methodology: AHP/ Fuzzy AHP	TOPSIS/ Fuzzy TOPSIS	Multi-objective optimization	VIKOR/ Fuzzy VIKOR	BOCR	Risk analysis	Shannon entropy	ARAS	Criteria
Adar et al. [46]	Ranking the wastewater processes based on contradictory criteria	*		*						Technical, cost, environmental
Çolak & Kaya [47]	Presenting a combined MCDM method to prioritize the renewable energy alternatives in Turkey	*	*							Quality of energy source, environmental, technical, technological, economic, sociopolitical
Shahnazari et al. [48]	identifying the relevant factors of municipal wastes to energy conversion technologies	*	*							Environmental, economic, technical
Adar [49]	Prioritizing different wastewater to energy conversion technologies	*				*				Benefit, opportunity, cost, risk
Ali et al. [50]	Using the best wastewater treatment technology in Pakistan				*					Non-beneficial and beneficial
Adar et al. [51]	Ranking the disposal methods for the wastes containing polychlorinated biphenyl	*					*			Environmental, technology, cost, and social/ergonomic
Wang et al. [52]	Selecting the best agricultural waste-to-energy conversion techlogy using life-cycle assessment	*	*							Environmental, technological, economic and social
Nkuna et al. [53]	Evaluating and ranking the thermo-chemical technologies for wastewater disposal and gas and electricity generation	*	*							Technical, economic
Kurbatova & Abu-Qdais [54]	Prioritizing the municipal solid waste to energy conversion technologies in mega cities	*								Environmental, technical, socioeconomic
ent research	Materia-technology priorization of industrial wastes in Iran							*	*	Environmental, social, economic, technical

Table 2b:

Authors	Applicability	Meeting the discharge standards	Investment/capital cost	Operational/maintenance cost	Land cost	Amount of sludge	Odor	Noise	Emmision	Sustainability	Energy Production capacity - energy Production	Efficiency	Technological maturity/ level	Reliability	Installed capacity	Land requirement	Need of waste disposal	Environmantal damage	Feasibility	Risk	Duration of preparation phase	continuity and redictability of performance	Availability of knowhow	Levelized energy cost	Service period	Compatibility to national energy policy	Slag	Employment rate	Waste separation cost	Waste collection cost
[46]	*	*	*	*	*	*	*	*	*																					
[47]									*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				
[48]									*				*			*											*	*		
[49]			*	*	*				*	*			*																	
[50]																*		*												
[51]			*	*	*		*	*	*											*			*							
[52]									*				*													*				
[53]			*	*									*																	
[54]			*	*					*		*							*					*							
Current research			*	*					*				*																*	*

Table 2c:

	Criteria																												
Authors	Accesibility industry growth	Ease of equipment access	Ease of technology use	Safety	Treatability of wastewater	Job provision/creation	Reducing energy prices	Suitability in local climate	Social resistance/public reaction	Occupational health and safety	Processing time	Manpower requirement efficiency	Energy consumption	Waste Production	Chemical requirement	Removal efficiency	COD discharge	Energy efficiency	Energy grade/ value	Development potential	Return on investment	Net present value	Payback period	Dependability	Public and occupational health	Sophistication of technology	Technology life-time	Process temperature	Production costs
[46]																													
[47]																													
[48]	*	*	*	*																									
[49]				*	*	*	*	*	*	*																			
[50]											*	*	*	*	*														
[51]			*						*							*				*									
[52]						*			*								*	*	*	*	*	*	*						
[53]													*											*					
[54]						*																			*	*			
Current research																		*	*								*	*	*

knowledge that may not be apparent from literature or mathematical calculations. Their input ensures that the selected criteria are relevant and applicable to real-world scenarios, thus bridging the gap between theoretical research and practical application. A list of the initial criteria is presented in Table 3.

Quantitative data for energy value (kJ/kg), technology lifetime (year), process temperature (centigrade), investment cost ($/kW), air pollution (kg CO_2/kWh), energy efficiency (%), technology maturity, operations, and maintenances costs ($/kWh), production cost ($/kWh), waste collection cost ($/ton) and waste separation cost ($/ton) were extracted from reports, books, and existing research.

3.1. Shannon entropy weighting method

To weigh the criteria, Shannon entropy was utilized. This method was introduced by Claude Shannon [98]. Shannon entropy effectively handles diverse datasets, providing a quantitative basis for decision-making and highlighting criteria with significant impacts based on empirical evidence. Its advantages include objectivity, flexibility, simplicity, and comprehensive analysis, making it an ideal choice for this study. The combination of expert opinions and Shannon entropy ensures a robust, data-driven evaluation of industrial waste for renewable energy generation. Entropy represents the level of uncertainty within a continuous probability distribution. Shannon's weighting approach is founded on the concept that the greater the data dispersion, the lesser the significance or weight of the index. This uncertainty is formulated as follows [99]:

$$E = S\{p_1, p_2, \ldots p_n\} = -K \sum_{i=1}^{n} [p_i \, Ln \, p_i] \tag{1}$$

In equation (1), k is a positive constant coefficient and is between zero and one. Shannon's entropy method is used to check the importance of criteria in multi-criteria decision-making. In this research, using primary data, which is shown in Table 4, the importance of indicators is calculated using the Shannon entropy method as follows:

Forming criteria-alternative matrix [100]:

$$DM = \begin{bmatrix} r_{11} & \ldots & r_{1n} \\ \vdots & r_{ij} & \vdots \\ r_{m1} & \ldots & r_{mn} \end{bmatrix} \tag{2}$$

In equation (2), m is the number of alternatives and n is the number of criteria. r_{mn} is the value of alternative i according to criterion j. Normalization is done as follows [101]:

$$P_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}; \quad \forall \, i, j \tag{3}$$

In equation (3), P_{ij} is the unscaled value of alternative i for criterion j. By using descaling, data becomes comparable and becomes dimensionless.

Entropy calculation [102]:

$$E_j = -k \left[p_{ij} \, Ln \, p_{ij} \right] ; \forall j \tag{4}$$

In equation (4), E_j is the entropy of j-th criterion and k is equal to $K = \frac{1}{\text{Ln m}}$. to calculate the degree of deviation [102]:

$$d_j = 1 - E_j ; \forall j \tag{5}$$

To weigh calculation [103]:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}; \quad \forall \, j \tag{6}$$

After calculating the weights using Shannon's entropy method, experts' opinion about the importance of each criterion was taken on a standard five-point Likert-scale ranging from very low: 1 to very high: 5. Then, an arithmetic mean was taken from the experts' opinions and combined with the weight of the same criterion obtained from Shannon's entropy method, as follows:

Calculating adjusted weights:

$$w'_j = \frac{\gamma_j \, w_j}{\sum_{j=1}^{n} \gamma_i w_j} \tag{7}$$

Table 3
The primary list of identified criteria

Row	Criterion	Reference
1	Accessible subsidies	[56]
2	Investment cost	[11,57–60]
3	Waiting time	[61]
4	Investment return period	[62]
5	Governmental incentives	[63]
6	Implementation cost	[40,56,59]
7	Economic value	[56,59]
8	Operation and maintenance cost	[11,57,59,60]
9	Technology costs	[61,64]
10	Technology lifetime	[61,65–68]
11	Energy value/resource potential	[69–72]
12	Cultivation cost	[73–75]
13	Production cost	[11,73]
14	Storage and transportation costs	[73,76]
15	Conversion rate	[73,77]
16	Risk intensity	[73,78]
17	Technical knowledge	[73,79]
18	Energy cost	[40,60,80]
19	Waste collection cost	[81,82]
20	Waste separation cost	[83]
21	Process temperature	[84,85]
22	Raw material accessibility	[86]
23	Technology maturity	[58–60,87,88]
24	Technical efficiency	[57,61]
25	Reliability	[56,59,87]
26	Energy efficiency	[56,60,66,89]
27	Security	[59,87]
28	Production capacity	[60,87]
29	Quantity of electricity generation	[87]
30	Accessibility to technologies	[90,91]
31	Possibility of operation and maintenance	[92,93]
32	Ecological effects	[59,61]
33	Air pollution	[94–96]
34	Social stability	[58]
35	Global effect	[59]
36	Soil quality	[73]
37	Water accessibility	[73]
38	Wildlife and plant diversity	[73]
39	Reducing the harvest of natural resources	[97]
40	Social acceptance	[56,57,60]
41	Job creation	[56,57,60]
42	Governmental support	[87]
43	Market size	[87]
44	Prosperity and energy security	[87]
45	Food competition	[87]

In equation (7), γ_j is the arithmetic mean of experts' opinion about the importance of each criterion, and w'_j is the adjusted weight of j-th criterion.

3.2. Ranking alternatives (technology-material prioritization)

Final prioritization is conducted based on eleven criteria across various aspects. For this, primary data (Table 4) and calculated weights (Table 5) are processed using the ARAS method. The ARAS method, introduced in 2010 by Zavadskas & Turskis [104], determines the relative efficiency of alternatives using a utility function proportional to the impact of values and weights. This method also considers the optimal value for each criterion, comparing each alternative's performance against these optimal values. ARAS method has several advantages over other MCDM methods. It is straightforward and easy to implement, allowing for the efficient integration of multiple criteria. ARAS provides a clear and transparent calculation process, enhancing the interpretability of results. Unlike some other MCDM methods, ARAS can handle both qualitative and quantitative data, making it highly versatile. Additionally, it emphasizes the relative performance of each alternative against the best possible solution, ensuring practical and realistic prioritization. This method's robustness in handling diverse and complex datasets makes it an ideal choice for evaluating and prioritizing

Table 4
Primary data

Waste type	Technology	Final yield	Technology lifetime	Energy efficiency	Energy value	Technology maturity	Process temperature	Technology investment cost	Air pollution	Waste collection cost	Waste separation cost	operation and maintenance cost	production cost
Organic wastes	Anaerobic digestion	Biogas	20	65	16,750	3	25–40	2570–6100	0.203	100	1	2.1–3.2	4.2
Wood wastes	Combustion	Heat	30	40	14,000	1	760–900	2170–4500	0.403	90	83	3.2–4.2	3.8–4.7
Sewage sludge	Anaerobic digestion	Biogas	20	65	16,600	3	30–38	2570–6100	0.41	238	1	2.1–3.2	4.2
Textile wastes	Combustion	Heat	30	40	17,000	1	760–900	2170–4500	0.7	200	208	3.2–4.2	3.8–4.7
Leather waste	Combustion	Heat	30	40	23,000	1	760–900	2170–4500	0.7	200	175	3.2–4.2	3.8–4.7
Paper and cardboard	Gasification	Synthesis gas	20	30	15,680	2	600–700	2140–5700	0.317	85	80	3–6	3
Plastic wastes	Gasification	Synthesis gas	20	30	45,000	2	600–700	2140–5700	0.044	165	400	3–6	3
Oil waste	Gasification	Synthesis gas	20	30	42,400	2	600–700	2140–5700	0.65	200	1	3–6	3

Table 5
The final weight of the criteria

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
w_j	0.0541	0.0736	0.2262	0.0669	0.3113	0.0064	0.1417	0.0475	0.0417	0.0231	0.0075
γ_j	0.1972	0.3262	0.5022	0.2273	0.6629	0.8254	0.1872	0.9122	0.3591	0.3521	0.2066
$w_j^{'}$	0.03052	0.05047	0.0777	0.03518	0.10258	0.12772	0.02897	0.14115	0.05556	0.0544	0.03197

industrial waste for renewable energy generation [104,105]. Additionally, the ARAS method allows for the ranking of an infinite number of alternatives, a feature not commonly available in other MCDM approaches [106].

Step 1) Forming a decision matrix (DMM)

$$DMM = \begin{bmatrix} x_{01} & \cdots & x_{0n} \\ \vdots & x_{ij} & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} ; i = \overline{0, m}; j = \overline{1, n} \tag{8}$$

x_{ij} shows the value of the i-th alternative concerning the j-th criterion. The first row of the DMM matrix shows the optimal values. If the criterion target is minimization, the minimum value among all available criteria values or an external optimal number can be selected. And if the desired value of the criterion is maximization, the maximum value among all criteria values or an optimum external value can be chosen [107]:

$$x_{0j} = \max x_{ij} \text{ if min value is preferable} \tag{9}$$

$$x_{0j} = \min x_{ij}^{*} \text{ if min value is preferable} \tag{10}$$

Step 2) Normalization

Different criteria have different measurement units. Multiple criteria in different dimensions, such as technical, economic, and environmental aspects, inherently measure different properties and impacts. Consequently, the use of different units is both logical and essential. Technical criteria require specific units to accurately describe physical properties. Economic criteria, like investment costs and production costs, use monetary units to quantify financial aspects. Environmental criteria need units that express environmental impacts. This standardization ensures clarity and consistency, allowing for comprehensive and precise analysis. The diverse measurement units maintain data integrity, prevent oversimplification, and ensure each criterion is evaluated appropriately, thereby facilitating a reliable and multidimensional assessment of the renewable energy potential from industrial waste. Before the DMM matrix can be used for calculations and establish comparability, the matrix needs to be first normalized, and the normalization in the ARAS method is done as follows [108]:

$$\overline{X} = \begin{bmatrix} \overline{x}_{01} & \cdots & \overline{x}_{0n} \\ \vdots & \overline{x}_{ij} & \vdots \\ \overline{x}_{m1} & \cdots & \overline{x}_{mn} \end{bmatrix} ; i = \overline{0, m}; j = \overline{1, n} \tag{11}$$

$$\overline{x}_{ij} = \frac{x_{ij}}{\sum_{i=0}^{m} x_{ij}} \text{ ; for positive criteria} \tag{12}$$

$$x_{ij} = \frac{1}{x_{ij}^{*}}; \quad \overline{x}_{ij} = \frac{x_{ij}}{\sum_{i=0}^{m} x_{ij}} \text{; for negative crite} \tag{13}$$

Step 3) Forming the weighted normal matrix: the normalized matrix is multiplied by the weights [109]:

$$0 < w_j < 1 \tag{14}$$

$$\sum_{j=1}^{n} w_j = 1 \tag{15}$$

$$\widehat{X} = \begin{bmatrix} \widehat{x}_{01} & \cdots & \widehat{x}_{0n} \\ \vdots & \widehat{x}_{ij} & \vdots \\ \widehat{x}_{m1} & \cdots & \widehat{x}_{mn} \end{bmatrix} ; i = \overline{0 - m}; j = \overline{1 - n} \tag{16}$$

$$\widehat{x}_{ij} = \overline{x}_{ij} \, w_j \text{ ; } i = \overline{0 - m} \tag{17}$$

In equation (17), w_j is the weight of criterion j, $\overline{x}_{ij}$ is the normalized value of alternative i in criterion j. optimization function S_i is presented as follows [110]:

$$S_i = \sum_{j=1}^{n} \widehat{x}_{ij}; i = \overline{0 - m} \tag{18}$$

K_i shows the relative effectiveness of each alternative according to the weight and real value of each alternative [111]:

$$K_i = \frac{S_i}{S_0} \text{ ; } i = \overline{m - 0} \tag{19}$$

The above-outlined method of data analysis and prioritization of alternatives uses the integrated weighting technique, allowing the simultaneous use of mathematical calculations and expert opinions. The validity of the expert opinions in this study is ensured through stringent selection criteria, including substantial experience and relevant qualifications in waste management, energy management, and environmental sciences. Each expert has a minimum of five years of professional experience, enhancing the reliability of their judgments. The diverse backgrounds of the experts from various reputable organizations ensure a comprehensive understanding of the issues, mitigating individual biases and promoting a holistic view. This diversity is crucial for assessing the complex nature of industrial waste management and renewable energy generation. Integrating expert opinions with quantitative methods enhances decision-making robustness, combining empirical rigor with practical insights for more accurate and applicable results [112,113].

4. Results and discussion

In this section, the research findings will be presented, which includes an analysis of all stages of formulation, from the identification of alternatives, criteria selection, and weighting of criteria to the final technology-material ranking.

4.1. Results of alternative identification

During the visits to industrial factories and companies, fifteen types of industrial wastes were identified, which included packaging wastes, paper waste, cardboard waste, tile and ceramics, textiles, sewage sludge, soap and detergents, construction mortar, slaughterhouse waste, rubber, cellulose waste, oil waste, lubricants, decommissioned machines, wood, plastic, metal, leather, organic wastes, and cement. These wastes originate from various production stages, including preparation, manufacturing, packaging, and shipping. Many of these materials are recyclable and reusable. For this research, eight types of industrial waste commonly found across most industries have been selected [55]. The selected alternatives for industrial waste include paper and cardboard, leather, textiles, sewage and sludge, oil, wood, organic, and plastic wastes.

4.2. Results of criteria selection

Table 3 shows the primary list of 45 criteria that were initially identified. Upon filtering the primary list criteria through the experts, the following 11 criteria were selected to be of significance for this study.

- **Energy value** (in kJ/kg): indicates the amount of energy obtained by burning 1 kg of industrial waste. Wastes that have a higher value are more suitable for energy production because they yield more energy per unit mass, making the conversion process more efficient and cost-effective [70–72].
- **Technology lifetime** (including gasification, combustion, and anaerobic digestion): Expressed in years and indicates the duration the technology works with adequate efficiency. Technologies with longer lifespans are preferred as they ensure sustained energy production and attract investors due to lower replacement costs over time [66–68,114].
- **Process temperature** (in degrees Celsius): Each process operates within a specific temperature range. Lower reaction temperatures are more desirable because they reduce the energy input required, thereby lowering operational costs and increasing overall process efficiency [11,84,85].
- **Technology maturity**: Maturity shows the stage of development and maturity of the technology in terms of points (from 1 to 3). Higher maturity levels indicate well-developed, reliable technologies that are ready for large-scale implementation, reducing the risks associated with unproven methods [88].
- **Operation and maintenance costs** (in $/kWh): It is in $/kWh and shows the amount of cost required for the maintenance and repair of the technologies used. Lower operational and maintenance costs enhance the economic feasibility of the technology over its lifecycle [11].
- **Production costs** (in $/kWh): Represent the variable costs associated with energy production per kilowatt-hour. This includes direct material and labor costs, which are crucial for determining the overall economic viability of the energy production process [11].
- **Waste collection cost** (in $/ton): Measures the cost to collect one ton of industrial waste. Efficient and cost-effective waste collection is essential for the feasibility of waste-to-energy projects, impacting the logistics and overall costs [81,82].
- **Waste separation cost** (in $/ton): Includes the cost required to separate industrial waste. Some wastes, like oil waste, do not require separation, making the energy conversion process simpler and less costly [83].
- **Air pollution** (in kg of CO_2 released/kWh produced): Indicates the amount of carbon dioxide emitted per kilowatt-hour of electricity produced. Technologies with lower emissions are preferred to minimize environmental impact and comply with regulations [72,94,95].
- **Energy efficiency**: Shows the ratio of energy output to energy input, expressed as a percentage. Higher efficiency indicates more effective energy conversion, making the technology more attractive and sustainable [65,66,89].
- **Investment cost** (in $/kW): Represents the capital required for each kilowatt of energy produced. Lower investment costs make technologies more accessible and financially viable for large-scale adoption [115].

4.3. Results of weighting the criteria

The arithmetic mean was utilized for interval data in the decision matrix due to its simplicity, ease of interpretation, and compatibility with the entropy method for weighting criteria. The mean provides a clear measure of central tendency, facilitating the normalization process necessary for handling different units across various criteria. Alternatives like the median, geometric mean, and harmonic mean were considered but were either less aligned with the entropy method or introduced unnecessary complexity. Using the arithmetic mean ensures consistency in evaluating data dispersion, which is crucial for the entropy-based weighting, thus enhancing the validity and robustness of the results [116–118].

Normalization is necessary in this study because the research criteria are measured in various units, making direct mathematical operations on the data impractical. By normalizing the data, they will become dimensionless, which simplifies subsequent calculations. The method for assigning weights to each criterion is based on the entropy value, which is influenced by the dispersion of the data: criteria with higher dispersion receive lower weights. For instance, according to Tables 4 and 5, C6 (investment cost) has the highest dispersion among all criteria, resulting in it being assigned the lowest weight. In contrast, C5 (process temperature) displays the least dispersion and is therefore given a higher weight.

After determining the criteria weights using Shannon entropy and collecting questionnaires from experts, an arithmetic mean was calculated for the experts' opinions on the importance of each criterion. These averages were then merged with the weights derived from the Shannon entropy method to obtain the final adjusted weights. Table 5 displays the Shannon entropy weights (w_j), the arithmetic means of experts' opinions (γ_j), and the calculated final weights (w_j').

Fig. 1 displays the adjusted weights of the studied criteria. According to Fig. 1, waste collection cost, at 14.11 percent, holds the highest overall importance among the criteria. This is logical, given the high costs associated with transportation and labor expenses. This factor makes the criterion particularly critical; if the total cost of collection and conversion exceeds the price of power, factories or companies might not be incentivized to dispose of their waste properly and may prefer to rely on fossil-based fuels instead.

Additionally, as shown in Fig. 1, technology investment cost, at 12.72 percent, is the second most important criterion. This significance is due to sanctions against Iran and high import tariffs set by the government, making the procurement of conversion technologies and machinery both difficult and expensive. Moreover, Iranian investors face significant financial challenges because they must cover machinery costs in US dollars while their revenues are in Iranian Rials (IRR). This results in financial losses due to fluctuating exchange rates and the devaluation of the IRR, which increases the cost burden. The disparity between the stronger dollar and weaker IRR, compounded by economic instability and sanctions, makes it difficult for investors to achieve a profitable return on investment. Limited access to international financial markets and banking restrictions further exacerbate these issues, increasing financial risks and potential losses [119]. Hence, investment cost is another crucial factor in the conversion of industrial waste to bioenergy.

The third important factor is process temperature, accounting for 10.25 percent of importance. Each technology requires a specific temperature to function optimally and produce the maximum amount of bioenergy. Achieving this initial required temperature consumes energy (in the form of gas, fuels, or electricity), which can lead to air pollution and high costs of bioenergy generation. Thus, the process temperature is crucial in deciding between different technologies and industrial wastes.

The least significant factor is related to air pollution, with only 2.89 percent importance. This result may be attributed to Iran's air pollution standards. Industrial machines must be tested and certified for their emission levels before importation, ensuring only approved machines are brought into the country. Therefore, a mandatory standard is already in place, reducing the emphasis experts place on this criterion. However, considering the sustainable responsibilities of manufacturers and decision-makers, this criterion will still be included in the ranking.

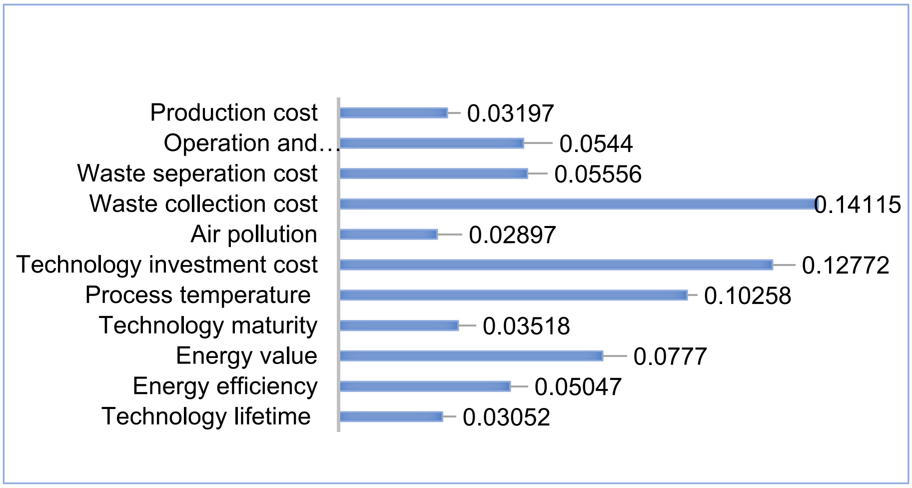

Fig. 1. The final weights of criteria.

4.4. Results of technology-material prioritization with ARAS method

In this section, the results of the final technology-material ranking are presented and analyzed. The Decision Matrix for the ARAS method is provided in Table 6. Subsequently, the utility values and final ranking results are depicted in Table 7.

As presented in Table 6, the objectives for criteria C1 (Technology Lifetime) to C4 (Technology Maturity) are maximization. Thus, the higher values of these criteria are deemed more desirable for decision-making. Higher values in these criteria indicate better performance and greater potential for long-term benefits, making them critical for effective decision-making [120,121]. Conversely, the objectives for criteria C5 (Process Temperature) to C11 (Production Cost) are minimized, meaning lower values are more favorable. The ideal value in this research is determined according to each criterion's objective; for positive criteria (maximization), the highest value is considered ideal, and for negative criteria (minimization), the lowest value is regarded as ideal.

Fig. 2 presents the final results of ranking the alternatives (technologies and wastes) using the ARAS method. According to the data shown in Table 7, the utility of the ideal alternative is the highest, set at 100 percent or 1. Subsequently, the utility of each alternative is calculated and compared to that of the ideal alternative. As indicated in Table 7, the leading alternative –organic waste combined with anaerobic digestion technology – achieves a score of 0.8505, making it the top choice. Organic waste, prevalent in varying amounts across all industries, constitutes the most common type of industrial waste. Koolivand et al. [55] reported that approximately 28.1 percent of all industrial wastes in Iran are organic, representing the largest fraction of all industrial wastes. Organic wastes hold significant potential for biogas production and can meet the energy needs of many factories in the industrial zone [122,123]. Utilizing the generated biogas within the industrial zone would reduce energy transfer loss, decrease environmental pollution, and support sustainable development in the industrial sector. Furthermore, anaerobic digestion, as the optimal technology for converting organic wastes to biogas, boasts the highest energy efficiency. Due to its technological maturity, it stands out as the best overall technology. Compared to other technologies, anaerobic digestion requires only 32.5 °C for the process temperature and produces the lowest emissions during bioenergy production. Additionally, organic waste entails no separation cost and is utilized in its mixed form. These factors are the primary reasons for selecting organic waste and anaerobic digestion as the best alternative.

Based on Table 7 and Fig. 2, sewage sludge combined with anaerobic digestion, scoring 0.7731, ranks second. In addition, plastic waste processed through gasification, with a score of 0.6941, is placed third. Sewage sludge, prevalent in various factories, possesses substantial potential for biogas generation. The advantages of anaerobic digestion have been previously discussed. Plastic waste, commonly found in different industries, particularly during packaging and delivery stages, can be effectively converted to biogas through gasification [124]. The process yields synthesis gas with a high energy value of 45,000 kJ/kg. Furthermore, the cost of converting plastic to synthesis gas is the lowest among all the evaluated alternatives.

According to the study by Torres-Lozada et al. [125], anaerobic digestion is favored for managing food waste because of its widespread social acceptance, its substantial impact in reducing greenhouse gas emissions, and its effectiveness in diminishing waste volumes. This aligns with the findings of this research, which emphasize the efficiency and sustainability of anaerobic digestion. Contrary to many studies that corroborate the findings of this research, numerous studies also explore alternative renewable energy sources like hydrogen. While investigating alternative energy solutions, it's crucial to recognize that hydrogen production, despite receiving significant attention from studies worldwide, continues to face substantial technological and infrastructural challenges [126]. Conversely, the results of this study indicate that anaerobic digestion, which leverages abundant organic waste, offers a less technologically complex and more cost-effective solution for immediate energy needs—particularly in industrial settings where waste availability is high, and energy demand is consistent.

It is worth noting that some previous studies outline new methods for energy storage that are crucial for managing intermittent energy production from renewables [127]. The approach of this study, which centers around the production and utilization of biogas, offers a streamlined alternative where energy is produced and consumed within close proximity, reducing the need for complex storage solutions. This integration of production and consumption not only optimizes energy use but also aligns with sustainable development goals by minimizing energy loss in transmission. This research directly contributes to sustainable development by effectively managing and utilizing industrial wastes, as evidenced by the ranking of organic waste and anaerobic digestion as top technologies. This approach not only reduces environmental pollution but also supports economic sustainability by lowering operational costs and leveraging existing waste streams. It should be noted that potential sources of error in this study include data quality and availability. It is possible that factories do not accurately report data on waste production. Although many efforts have been made to validate the data as much as possible, inaccuracies may still occur. Such errors can lead to suboptimal policy decisions, slowing progress toward climate change targets and undermining confidence in policy strategies.

Table 6
Decision matrix of ARAS method

Waste type	Technology	Final yield	Technology lifetime	Energy efficiency	Energy value	Technology maturity	Process temperature	Technology investment cost	Air pollution	Waste collection cost	Waste separation cost	Operation and maintenance cost	Production cost
Objective			max	max	max	max	min	min	min	min	min	min	min
Ideal value = A_0			30	65	45,000	3	32.5	3335	0.203	85	1	2.65	3
Weight (W_j)			0.0541	0.0736	0.2262	0.0669	0.3113	0.0064	0.1417	0.0475	0.0417	0.0231	0.0075
Modified weight (w_j')			0.03052	0.05047	0.0777	0.03518	0.10258	0.12772	0.02897	0.14115	0.05556	0.0544	0.03197
Organic wastes	Anaerobic digestion	Biogas	20	65	16,750	3	32.5	4335	0.203	100	1	2.65	4.2
Wood wastes	Combustion	Heat	30	40	14,000	1	830	3335	0.403	90	83	3.7	4.25
Sewage sludge	Anaerobic digestion	Biogas	20	65	16,600	3	34	4335	0.41	238	1	2.65	4.2
Textile wastes	Combustion	Heat	30	40	17,000	1	830	3335	0.7	200	208	3.7	4.25
Leather waste	Combustion	Heat	30	40	23,000	1	830	3335	0.7	200	175	3.7	4.25
Paper and cardboard	Gasification	Synthesis gas	20	30	15,680	2	650	3920	0.317	85	80	4.5	3
Plastic wastes	Gasification	Synthesis gas	20	30	45,000	2	650	3920	0.044	165	400	4.5	3
Oil waste	Gasification	Synthesis gas	20	30	42,400	2	650	3920	0.65	200	1	4.5	3

Table 7
Results of ranking

Alternatives	S_i: Score of ARAS method	K_i: Utility	Rank
A0	0.2091	1.0000	-
A1	0.1778	0.8505	1
A2	0.0550	0.2629	7
A3	0.1617	0.7731	2
A4	0.0503	0.2406	8
A5	0.0561	0.2682	6
A6	0.0594	0.2840	5
A7	0.1451	0.6941	3
A8	0.0856	0.4092	4

5. Conclusion

The challenges of energy supply in large industrial zones, where power outages can significantly affect machinery and operations, are mitigated through the utilization of industrial waste for bioenergy production [128]. This study assessed the potential of various industrial wastes and technologies for bioenergy generation. Relevant alternatives and criteria were identified through literature reviews and questionnaires, with their significance determined by integrating mathematical calculations with expert insights. A comprehensive waste-technology analysis was then conducted using the ARAS method.

Key findings of this study include.

- The identification of eleven crucial criteria: operational and maintenance costs, air pollution, technology investment cost, technology maturity, energy value, energy efficiency, process temperature, technology lifetime, production cost, waste collection cost, and waste separation cost. Notably, the criteria of process temperature, technology lifetime, production cost, waste collection cost, and waste separation cost were incorporated for the first time in this context, reflecting the novel aspects of this research.
- The weighting results revealed that waste collection cost (14.11 %), technology investment cost (12.77 %), and process temperature (10.25 %) are the most significant criteria.
- Organic waste combined with anaerobic digestion technology ranked highest due to its potential for bioenergy production, technological maturity, efficiency, and lower process temperatures, followed by sewage sludge with anaerobic digestion and plastic waste processed through gasification, valued for their efficiency and environmental benefits.

The novelty of this study lies in the introduction of five new evaluation criteria that have not been previously considered in the context of assessing industrial waste for renewable energy generation, particularly in developing countries. These criteria address critical gaps in the existing literature on waste-to-energy technologies, such as the specific impact of process temperature on the efficiency and economic viability of energy conversion technologies, the longevity of technology for sustainable waste-to-energy conversion, and detailed cost analysis of production, collection, and separation of waste.

While the primary focus of this study is limited to the context of developing countries, particularly Iran, the methodologies employed, such as the ARAS method for evaluating industrial waste potential for bioenergy generation, provide a robust framework that can be adapted to different technological, economic, and regulatory environments globally. This study's findings can inform policymakers and technologists in developed countries about scalable and adaptable waste-to-energy technologies. However, to ensure the accuracy and applicability of these results across various national contexts, future research should include cross-comparative studies that explore how these methods and technologies perform in both developing and industrialized countries, addressing specific variations in industrial waste characteristics and bioenergy production efficiency.

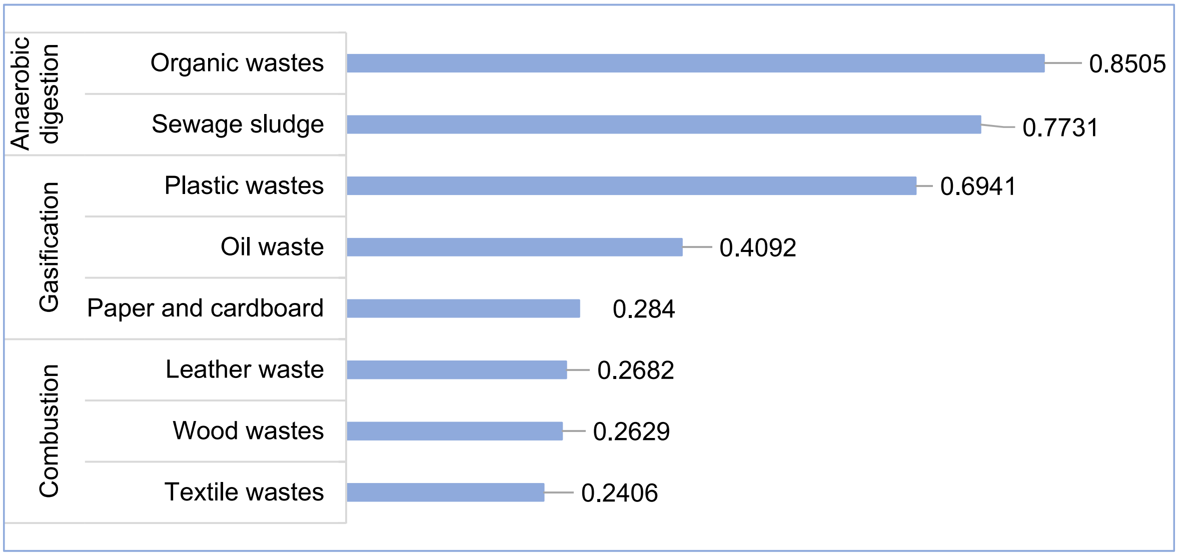

Fig. 2. The final results of waste-technology ranking.

CRediT authorship contribution statement

Fatemeh Najafi: Conceptualization, Methodology, Software, Validation. **Mostafa Kazemi:** Data curation, Writing – original draft. **Ali Mostafaeipour:** Visualization, Investigation, supervising. **Phoolenrda Mishra:** Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to thank the organizations for providing the relevant data and the experts for supplying the assessment questionnaire. There was no funding and grant for this research work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2024.114818.

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