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Review

Waste-to-Energy Technologies in Saudi Arabia: A Case Study and Review of Waste Conversion and Energy Recovery

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Abstract

This study provides a comprehensive evaluation of waste-to-energy (WtE) technologies in Saudi Arabia, focusing on municipal solid waste (MSW) across various cities, in alignment with Saudi Vision 2030. Saudi Arabia generates approximately 16 million tons of MSW annually, primarily composed of organic matter (37–57%), followed by paper (11–28%) and plastics (5–36%). According to Vision 2030 projections, MSW generation is expected to increase to approximately 30 million tons per year by 2033, driven by population growth, urbanization, and increased tourism activities. Waste quantities notably increase during the Hajj and Ramadan seasons. The study assesses three main WTE technologies: biochemical, chemical, and thermochemical processes. Anaerobic digestion (AD) effectively converts organic waste into biogas with a methane content of 60% to 80%, potentially yielding up to 2.99 TWh annually. Transesterification efficiently targets fats in waste, generating around 244.2 GWh per year. Thermochemical processes, including incineration, gasification, and pyrolysis, are suitable for high-calorific waste. Incineration can significantly reduce waste volume and generate up to 2073 MW while lowering GHG emissions. Economic assessments reveal that biochemical methods are the most cost-effective for managing organic waste, while thermochemical methods, despite higher capital costs, achieve significant energy recovery. Integrating WTE technologies with recycling is crucial for enhancing environmental sustainability and supporting Saudi Arabia's Vision 2030 objectives.

Keywords: municipal solid waste; Saudi Arabia; Saudi Vision 2030; waste management; waste technologies; waste-to-energy; waste-to-fuel

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1. Introduction

The global challenge of waste management has reached alarming levels, exacerbated by rapid urbanization, population growth, and increasing industrial activities [1,2]. The swift migration from rural to urban settings, in tandem with rapid industrialization, has significantly escalated the volume and diversity of municipal solid waste (MSW), posing substantial threats to environmental integrity and human health [2]. This issue is particularly pronounced in affluent nations, where modern consumption patterns result in higher

waste outputs, highlighting the urgent need for immediate attention and strategic management. MSW comprises various materials, including household refuse, garden waste, and commercial and institutional by-products. The mismanagement of these waste streams can lead to severe environmental issues such as air and water pollution, soil contamination, and the proliferation of greenhouse gas (GHG).

In Saudi Arabia, extensive reserves of crude oil have established the Kingdom as one of the largest oil producers worldwide [3–5]. Oil and natural gas serve as the primary energy sources, mainly for transportation and electricity needs [2,6]. As noted in the Statistical Review of World Energy, Saudi Arabia's oil consumption reached approximately 3.96 million barrels per day (bbl/d) in 2024, representing a 1.5% growth compared to 2023 and accounting for around 3.8% of global oil consumption, as shown in Figure 1 [6]. Figure 1 displays the trend of total oil consumption in Saudi Arabia from 2014 to 2024. Initial growth from 2014 to 2016 peaked at 4.1 million Bbl/d, followed by a decline in subsequent years, with notable drops in 2017 and 2019. This decline reflects various economic factors and shifts toward sustainable energy practices. From 2020 onwards, there is a slight recovery, reaching 3.959 million Bbl/d in 2024 [6,7].

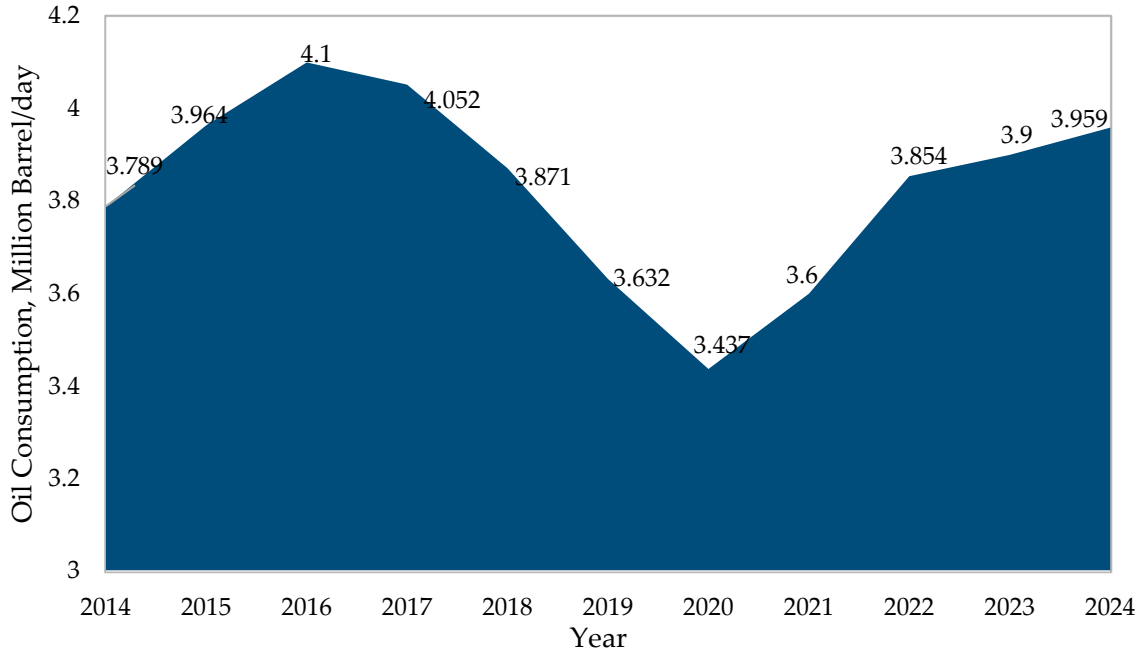


Figure 1. Total liquids consumption in Saudi Arabia adapted from [6,7].

The continued reliance on fossil fuels in Saudi Arabia highlights the urgent need for exploring alternative energy strategies alongside sustainable waste management practices. The Kingdom has experienced a rapid increase in energy demand driven by population growth and socio-economic development [8]. The population rose from 20.48 million in 2000 to 34.83 million in 2020, with projections suggesting it could reach around 70 million by 2050 [9,10]. This demographic shift has led to a significant increase in per capita energy consumption, which grew from 31.24 MWh in 2000 to over 40 MWh in recent years [10]. Electricity consumption has similarly escalated, increasing from 126 billion kWh in 2000 to about 315 billion kWh in 2017, with expectations nearing 400 billion kWh within the next decade [11]. Despite the availability of sufficient energy supply, the sector remains heavily dependent on fossil fuels, resulting in a substantial environmental footprint [9,10]. Carbon dioxide (CO_2) emissions surged from 235 million tons in 2000 to over 530 million tons in 2017, primarily due to the power generation and transport sectors [10].

In parallel, high industrial activity levels have intensified air pollution and caused a dramatic rise in waste generation [2]. The Kingdom's population is estimated to reach around 35.3 million by 2024 [9], further exacerbating the waste management challenge, with projected annual waste generation reaching approximately 60.88 million tons [12,13]. Notably, about 18.9 million tons of this total is classified as MSW, constituting roughly 31% of all waste produced [12]. This waste primarily consists of food waste, plastics, metals, and construction debris, underscoring the critical need for comprehensive waste management solutions.

Saudi Arabia currently generates more than 16 million tons of MSW annually, with per capita generation rates ranging between 1.4 and 1.75 kg per person per day [2,14]. In line with Saudi Vision 2030, national projections indicate that MSW generation could reach approximately 30 million tons per year by 2033, reflecting rapid urban development, increased consumption patterns, and growth in religious and leisure tourism [14,15]. In response to these challenges, the Kingdom aims to enhance its energy diversification by expanding its installed electricity capacity to 120 GW by 2032 [11]. This effort includes accelerating the deployment of renewable energy sources such as solar, wind, biofuels, and waste-to-energy (WtE) technologies, all aimed at reducing GHG emissions and promoting sustainable development [11].

Current practices in Saudi Arabia primarily rely on the disposal of MSW in landfills, where approximately 99% of waste is buried and only about 1% is recycled [2,16]. This heavy dependence on landfilling, often conducted without comprehensive environmental safeguards, contributes to GHG emissions and heightens public health risks [16]. In contrast, countries like China and EU member states have implemented more diversified waste management practices that balance recycling, composting, and energy recovery [17]. Figure 2 illustrates the waste management approaches in these regions, highlighting that China utilizes a management mix of approximately 74% landfilling, 10% recycling, 2% composting, and 14% incineration. Similarly, EU countries demonstrate a balanced approach, with 41% of MSW landfilled, 27% recycled, 16% composted, and 16% treated through incineration with energy recovery [2,17].

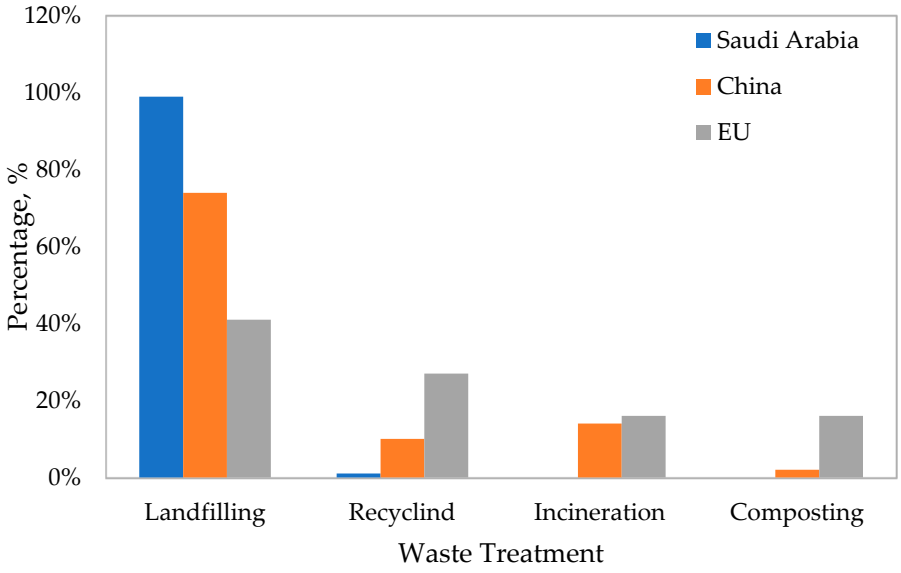


Figure 2. Different waste management practices in Saudi Arabia, China, and the EU [2,17].

The MSW generation is a rapidly increasing challenge that contributes to severe pollution and environmental degradation in many urban areas of developing countries [18]. Globally, the solid waste sector accounts for 18% of methane (CH_4) emissions and 3–4%

of overall GHG emissions [18]. In the waste management hierarchy, landfilling is the least favorable disposal option, reserved for after all other methods, such as prevention, reuse, recycling, composting, and energy recovery, have been exhausted [19,20]. The mismanagement of waste not only results in significant environmental degradation but also leads to the loss of valuable natural resources and energy. To address these pressing issues, the Kingdom has explored innovative solutions for transforming its waste management landscape through WtE technologies. These technologies can effectively recover energy from MSW, significantly reducing landfill volumes while generating renewable energy [21]. The thermal treatment of MSW can produce between 500 and 600 kWh of electricity per ton combusted [1,22]. Moreover, each ton of MSW combusted in a WtE plant can reduce fossil fuel use by an amount equivalent to about 0.25 tons of coal [23]. This shift aligns with the overarching goals of Saudi Arabia's Vision 2030, supporting objectives related to energy diversification and environmental sustainability.

The Kingdom's Waste Management Law, enacted in 2021, serves as a regulatory framework guiding the development and implementation of sustainable waste management practices [24]. This law emphasizes prioritizing recycling and resource recovery, mandating waste segregation at the source, and establishing protocols for the safe disposal of residual waste. The application of WtE technologies provides numerous benefits, including the reduction in landfill requirements, renewable energy generation, and the mitigation of environmental impacts associated with traditional waste disposal methods [25]. Furthermore, it stimulates economic growth by creating job opportunities in the renewable energy sector and enhancing local capabilities in waste management [25].

This comprehensive review aims to explore the potential of WtE technologies within the Saudi Arabian context, examining the specific challenges and opportunities the Kingdom faces. It analyzes the economic implications of adopting WtE as a cornerstone of a sustainable waste management strategy, as well as the environmental benefits that arise from its implementation. By synthesizing global best practices and addressing the specific needs of the Kingdom, this study seeks to contribute valuable knowledge to the fields of waste management and renewable energy. Ultimately, the successful adoption of WtE solutions could play a critical role in redefining the Kingdom's relationship with waste, fostering a sustainable future that harmonizes economic performance with environmental stewardship.

Despite extensive literature on MSW generation and management globally, there was a significant lack of resources specific to Saudi Arabia. This deficit in accurate data and recommendations contributed to inefficient MSW management in the country. This study aimed to provide a systematic review of WtE development in Saudi Arabia, focusing on MSW component-based characteristics from various cities, technology applicability, and energy recovery potential. The review analyzed key waste streams, including municipal and medical waste, evaluated the suitability and performance of various WtE technologies within the Saudi context, and synthesized existing feasibility studies to assess WtE's contribution to the national energy mix. Furthermore, it reviewed the implementation status of WtE projects and identified key challenges and future research needs, aligning with Vision 2030. By addressing existing management techniques, including thermal and chemical processes.

2. Materials and Methods

This study employed a structured literature review to examine the current state of WtE technologies and initiatives in Saudi Arabia, covering various cities. The methodology was designed to provide both quantitative and qualitative insights into the WtE landscape. The Scopus database was selected as the primary source due to its broad international coverage,

reliable citation tracking, and extensive inclusion of journals related to environmental science, energy, and waste management [26].

A systematic literature search was conducted using a structured query string and targeted keywords: ("Saudi Arabia" OR "KSA") AND ("Waste to Energy" OR "Waste to Fuel" OR "WtE" OR "WtF" OR "Gasification" OR "Incineration" OR "Refuse Derived Fuel" OR "RDF" OR "Biomethanation" OR "Pyrolysis" OR "Plasma"). The search was limited to publications from 2013 to 2025, in English, and to relevant document types (articles, reviews, conference papers, conference reviews, and book chapters). The initial search retrieved 166 documents.

To minimize selection bias, inclusion and exclusion criteria were clearly defined. Only studies directly addressing WtE in Saudi Arabia were included. The dataset was further filtered by peer-review status and source type, focusing on journal articles and conference proceedings, resulting in 98 documents. A meticulous manual review of titles, abstracts, and keywords was performed to ensure relevance, producing a final dataset of 81 documents.

While most technical and economic assessments in the reviewed studies were based on modeled scenarios or small-scale experiments, few studies provided large-scale, long-term operational data from Saudi Arabia's heterogeneous urban waste environments. This limitation was carefully considered in the analysis, and all results are interpreted. All selected studies were systematically analyzed to extract insights into WtE technologies, implementation challenges, and policy frameworks in Saudi Arabia. This approach ensures transparency in keyword selection, minimizes bias in literature inclusion, and provides a solid foundation for understanding current trends and gaps in WtE research within the country.

3. Waste Generation and Characteristics in KSA

3.1. MSW Generation and Distribution in KSA

The generation of MSW in KSA has notably increased over recent decades, driven by rapid population growth, urbanization, economic development, and evolving consumption patterns [27]. The management of MSW in KSA is primarily overseen by municipal authorities, with an emphasis on landfilling as the prevalent method for waste disposal [27–29]. Although this method has historically provided economic advantages, it has constrained the development of organized recycling and resource recovery initiatives [27]. Presently, large-scale recycling efforts are largely limited to the informal recovery of cardboard and metals, with only a few cities, such as Madinah, implementing limited source separation and recycling programs [29,30].

KSA produces approximately 16 million tons of MSW annually, translating to an average per capita generation rates ranging between 1.4 and 1.75 kg per person per day [2,14]. Continued reliance on landfilling has led to increased environmental pressures, with estimates indicating that landfill space requirements will exceed 3 million m^2 annually [27]. As many existing disposal sites are reaching the end of their operational lifespan, it is anticipated that landfill capacity will be surpassed [27]. These issues underscore the urgent necessity for alternative and sustainable waste management strategies, particularly those that can facilitate energy recovery from waste.

The composition of MSW in KSA varies among cities, reflecting disparities in lifestyle, socio-economic activities, and seasonal influences. As illustrated in Figure 3, organic waste constitutes the predominant fraction of MSW in most Saudi cities, ranging from 37% at the national level [5,29] to as high as 57.2% in Riyadh [31,32] and 55.4% in Madinah [14]. Makkah also displays a significant organic content (50.6%) [27,33,34], with a notable decrease during the Hajj season (38.96%) [27,35], correlated with a substantial increase in

plastics (36.48%) [27,35]. This variation highlights the substantial influence of seasonal mass gatherings on waste characteristics (Figure 3).

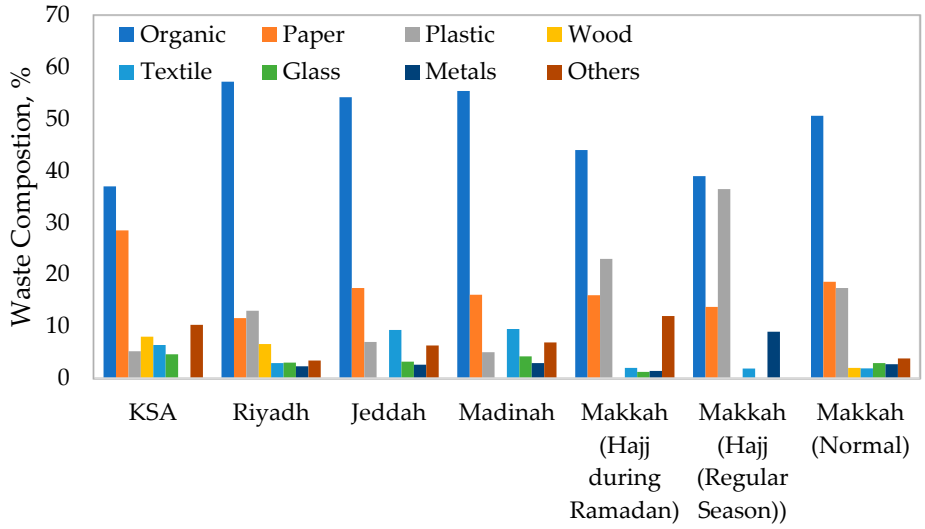


Figure 3. MSW composition in different cities of KSA.

Paper is the second major component of MSW in KSA, representing 28.5% at the national level [5,29], with smaller percentages observed in cities such as Riyadh (11.6%) [31,32] and Makkah (18.6%) [33,34]. Plastic waste exhibits considerable variability, ranging from 5.2% nationally [5,29] to 18% in Jeddah [14], peaking at 36.48% during the Hajj in Makkah [35]. This elevated plastic percentage is primarily linked to the extensive use of disposable packaging and bottled water during pilgrimage periods (Figure 3). Additionally, other combustible fractions, such as wood and textiles, contribute a non-negligible portion to MSW, with wood comprising up to 15% in Jeddah [14] and textiles varying from 1.9% to 6.4% across reported cities [5,33,34]. In contrast, non-combustible materials, including glass and metals, form a smaller fraction of the waste stream. Glass content ranges from 2.9% to 4.6% [5,31,32], while metals (including aluminum) typically remain below 7% in most municipal areas, reflecting limited contributions to energy recovery but potential significance for material recycling (Figure 3).

The predominance of organic waste, paper, plastics, textiles, and wood illustrates considerable potential for WtE applications in KSA. Nevertheless, the high organic fraction is generally associated with elevated moisture content, which can negatively impact the net calorific value of MSW [29]. Prior studies have indicated that food waste in KSA is characterized by high moisture contents (38.4%) and significant proportions of carbohydrates (25.6%%), proteins (17.3%), and fats (15.3%), all of which markedly influence its thermal behavior and energy yield [29]

Furthermore, the persistent disposal of organic-rich waste in landfills has significantly contributed to CH_4 emissions, with the waste sector accounting for approximately 66% of the country's total CH_4 emissions, estimated at about 1.3 thousand Gigagram (Gg), predominantly from sanitary landfills [36]. The MSW composition data presented in Figure 3 illustrate that Saudi cities generate waste streams rich in combustible materials, particularly organic matter and paper, with notable spatial and seasonal variability. These characteristics highlight the critical importance of accurately quantifying waste composition and distribution as a prerequisite for estimating energy content (kW/kg of MSW) and for selecting appropriate WtE technologies that can effectively process the predominant waste fractions in KSA [5].

3.2. Regional and Seasonal Variations in MSW Composition in KSA

MSW Composition During Hajj and Umrah Seasons

The annual Hajj pilgrimage draws approximately 3 million Muslims to Makkah, resulting in substantial quantities of MSW generated without sufficient separation or management [27]. Shahzad et al. [37] estimate that the daily waste output during Hajj ranges from 3100 to 4600 tons. A significant portion of this waste is produced in Mina, where pilgrims typically spend four to five days, leading to an estimated 17,000 tons of MSW being deposited in landfills without resource recovery [15]. At the Grand Mosque, daily waste generation exceeds 200 tons [15].

The ritual animal sacrifices associated with Hajj pose considerable challenges for waste management [38]. During Umrah, particularly in Ramadan, waste generation can peak at approximately 190 tons, primarily from food waste [16]. The cumulative waste from Umrah visitors and local residents may total around 5000 tons. On average, Makkah generates roughly 2400 tons of MSW daily, with spikes exceeding 3000 tons during Ramadan and reaching 4500 tons during Hajj [38]. Peak waste generation typically occurs during the last ten days of Ramadan and from the 8th to the 13th of Dhu al-Hijjah, aligning with the Hajj period [39]. In 2014, total MSW generated was approximately 950,000 tons, consisting of about 900,000 tons from residents and 90,000 tons from pilgrims [34,37]. The waste produced during Hajj is varied, comprising household and biological waste [40]. The waste composition during Umrah resembles that of the local population, influenced by visitor interactions, with notable contributions from food disposal and single-use utensils [38]. The extreme heat during Hajj and Umrah exacerbates waste management challenges, particularly due to the significant volume of disposable plastic items, including Zamzam water cups [27]. Additionally, the environmental impact of disposing of animal by-products from ritual sacrifices is considerable [39].

The waste management system in Makkah mirrors those in other Saudi cities, encompassing waste collection, transfer, and landfill disposal [38]. Collection efforts are labor-intensive and costly, especially during Hajj and peak Umrah periods. Waste is collected from street containers three times a day in central areas and less frequently in other locations [27]. Following collection, waste is transported to transfer stations or directly to landfills using compactor trucks [27]. Makkah operates six transfer stations, each with a capacity of 140 m^3, designed to consolidate waste for disposal in larger landfill containers [38]. However, similar to many landfills in Saudi Arabia, Makkah's landfill is deficient in leachate and gas collection systems and protective liners, raising significant concerns about environmental contamination [39]. The landfill is organized into cells that can fill within a week, necessitating rapid landfill expansion and posing regulatory challenges [27]. Effective landfill management is crucial, especially given the absence of alternative waste treatment options. Recycling efforts predominantly rely on the informal sector, which recycles materials such as metals, cardboard, and plastics, achieving only about 10% of total waste recycling [38]. Overall, the waste generated during Hajj and Umrah underscores the urgent need for enhanced waste processing strategies in Makkah to mitigate environmental impacts while accommodating the demands of religious tourism.

3.3. Energy Content of MSW Components

The heating value and overall energy recovery potential of MSW are crucial parameters in assessing the viability of WtE technologies [2]. Research has shown that the performance of waste incineration is significantly affected by the organic fraction, moisture content, and ash content present in the waste stream [41]. Effective combustion can occur when the waste exhibits relatively low moisture levels combined with sufficient combustible material, even when higher ash content is present [42]. These factors collectively determine

the efficiency of MSW processing without reliance on auxiliary fuels [42]. Table 1 illustrates the typical energy content of various waste types expressed in Btu/lb. [43].

Table 1. Energy content of various type of MSW [43].

Type of Waste	Energy Content, Btu/Ib
Mixed paper	6800
Mixed food waste	2400
Mixed green yard waste	2700
Mixed plastic	14,000
Rubber	11,200
Leather	8000
Textiles	8100
Demolition Softwood	7300
Waste hardwood	6500
Coal	12,300
Fuel, oil	18,300
Natural Gas	23,700

As shown in Table 1, it is evident that plastics have the highest calorific value at 14,000 Btu/lb., approaching or even exceeding that of conventional fossil fuels like coal (12,300 Btu/lb.). This high energy density signifies that plastics can play a crucial role in energy recovery processes [43]. In contrast, organic materials like food waste and green yard waste show much lower energy values, with measurements of 2400 Btu/lb. and 2700 Btu/lb., respectively. This disparity is primarily due to their elevated moisture content and lower levels of fixed carbon, which diminish their combustion efficiency [19]. While these organic fractions do not provide substantial energy when compared with conventional fossil fuels such as coal, fuel oil, and natural gas, their abundant and continuous generation in urban environments renders them a significant resource for renewable energy applications [19,43]. The actual energy recovery potential is contingent upon the relative abundance of each component within the MSW stream and their respective moisture and dry mass fractions [2]. The variability in energy content among different waste fractions underscores the importance of effective waste segregation. By focusing on high-energy materials such as plastics, rubber, and textiles, alongside organic waste, WtE technologies can optimize their energy output and contribute to a reduction in fossil fuel dependency.

Table 2 offers a comprehensive look at the composition of MSW specifically in Saudi Arabia. It details the percentage makeup of each waste component by wet mass, in addition to their moisture content, dry weight percentages, and energy contents expressed in kWh per kilogram.

Table 2. Composition and energy content of MSW components in the KSA (higher heating value (HHV) basis) [2,5,43].

Component	Composition (% by Wet Mass)	Dry Waste (%)	Moisture Content (%)	Energy Content (kWh/kg, Waste-HHV)	Energy Content (kWh/kg, Material)
Organic	37	17.76	52	0.7476	1.551
Paper	28.5	26.79	28.5	0.0453	4.394
Wood	8	6.48	19	0.4551	4.726
Textile	6.4	5.504	14	0.3000	5.199
Plastic	5.2	5.096	2	0.5246	9.046
Glass	4.6	4.508	2	0	0
Others	10.3	9.373	9	0.7476	3.36

As shown in Table 2, organic waste constitutes the largest segment of MSW in Saudi Arabia, representing 37% by wet mass. Despite its high moisture content of approximately 52% and relatively low energy density (1.551 kWh/kg), this organic fraction significantly contributes to overall energy potential, yielding around 0.748 kWh/kg of wet MSW [2,5,43]. These characteristics render organic waste particularly suitable for biochemical conversion processes such as anaerobic digestion (AD) [44], as well as thermochemical processes like pyrolysis with appropriate pre-treatment [45].

In terms of energy content, paper emerges as the second-largest component at 28.5% of MSW, with material-based energy values of about 4.394 kWh/kg. Its moderate moisture content allows paper to contribute significantly to the overall heating value of MSW, making it fit for combustion and other thermal recovery methods [2,5,43]. The wood and textile fractions also demonstrate moderate energy recovery potential, although their effective contributions are influenced by moisture content [2,5,43].

While plastics only account for 5.2% of the total waste mass, their high energy content of 9.046 kWh/kg affirms their vital role in maximizing the calorific value of mixed MSW [19,43]. Thus, plastics significantly enhance the overall heating value of mixed MSW, making them well-suited for thermochemical WtE technologies, including incineration [46], gasification [47], plasma arc gasification [48], and Refuse-derived fuel (RDF) production [19,49]. On the other hand, glass is classified as an inert material and does not participate in energy recovery, highlighting the necessity of considering waste characteristics during processing [5,43]. The "Others" category encompasses various combustible materials that exhibit intermediate heating values, reflecting the heterogeneous nature of the waste stream [5,43].

The analysis of Tables 1 and 2 illustrates that the energy recovery potential of MSW in Saudi Arabia is primarily driven by organic waste and plastics. While organic waste dominates in terms of mass, plastics play a crucial role in enhancing the overall energy content of the waste stream. Additionally, contributions from paper, textiles, and wood further bolster the viability of MSW as a sustainable energy source.

4. WtE Conversion Technology

WtE technologies are innovative solutions that transform MSW into usable energy while addressing significant environmental concerns associated with waste management. These technologies help reduce the volume of waste sent to landfills and contribute to energy production, aligning with sustainability goals. In Saudi Arabia, the expansion of WtE facilities is crucial due to rising waste generation rates and limited landfill space [29]. The initiatives outlined in Vision 2030 underscore the importance of integrating WtE systems into the nation's energy and waste management strategies [29,33,50]

The WtE conversion technologies represent a significant advancement in sustainable energy production by transforming non-recyclable waste into valuable energy forms such as heat, electricity, and transport fuels [33,51,52]. This shift redefines waste from being a burden to serving as a productive feedstock, thereby alleviating landfill pressures and creating pathways for converting waste into useful products like fertilizers and energy [19,51]. The WtE conversion process encompasses a variety of waste types, including semi-solid, liquid, and gaseous forms [19], employing methodologies such as thermochemical, biochemical, and physicochemical technologies [15,17].

This integration of WtE technologies aligns with Saudi Arabia's broader energy sustainability goals, enhancing waste management practices and contributing to a more diversified energy portfolio [53,54]. By embracing these innovative technologies, the Kingdom is taking proactive steps toward a cleaner environment and a sustainable energy future.

4.1. Thermochemical WtE Conversion Technologies

Thermochemical conversion technologies offer an effective means for transforming MSW into renewable energy sources. Key processes include incineration [55], pyrolysis [16], plasma arc gasification [56], and gasification [57], each employing high-temperature treatment to produce energy-rich gases, oils, and solids for energy applications [31]. Incineration, the most widely applied technique, involves engineered combustion of waste materials at high temperatures to break down waste, primarily generating heat and electricity [25,57]. In contrast, pyrolysis and gasification occur under controlled conditions with limited oxygen [25,57]. Pyrolysis decomposes organic materials into gas, liquid, and solid products [16], whereas gasification primarily converts organic matter into syngas, a versatile energy source suitable for power generation or as a chemical feedstock [25,57,58]. These processes apply sufficient thermal energy within a closed vessel, breaking molecular bonds and decomposing waste into smaller molecules [19]. Following this decomposition, a recombination phase occurs where carbon and hydrogen (H_2) atoms released from the waste combine with oxygen, yielding more energy than was consumed initially [59]. This crucial step not only enhances energy recovery but also neutralizes harmful waste components [19,60].

The varying operational conditions of these thermal WtE technologies lead to different product yields and applications, with gasification, characterized by high temperatures and rapid heating rates, promoting the generation of gas products [29,61]. The standard conditions and synthesized products of various thermal WtE processes are illustrated in Figure 4. The efficiency of thermochemical conversion technologies in managing diverse waste types underscores their significance for effective energy recovery, a potential actively explored in contexts such as Saudi Arabia [16,55,57].

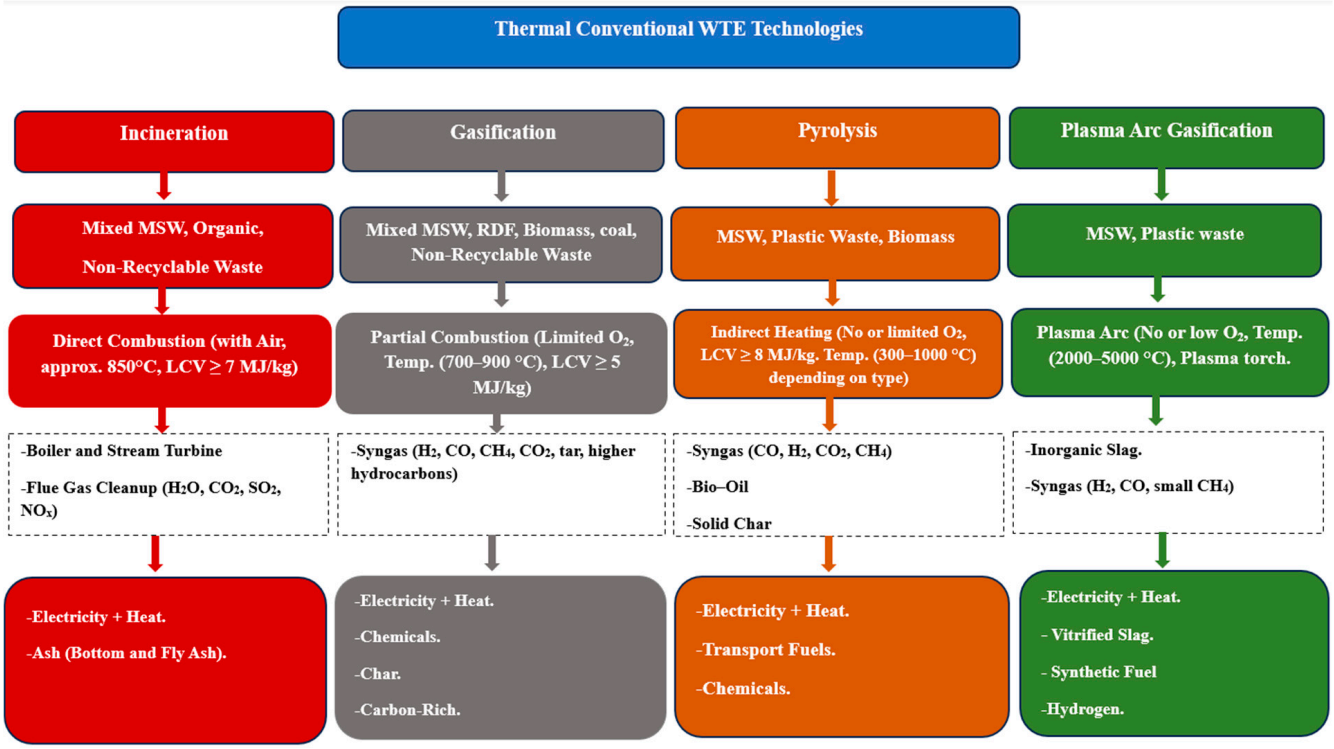


Figure 4. Flowchart of the thermal WtE process.

4.1.1. Incineration

Incineration is a widely adopted waste management technology that involves the complete combustion of organic materials in MSW [2]. This method is effective for recovering energy from waste that cannot be recycled, thereby reducing landfill dependency [19]. This method involves the high-temperature oxidation of organic materials, resulting not only in a significant reduction in waste volume but also in the generation of thermal energy, which can be converted into electricity [19]. The relevance of incineration has become increasingly evident, especially in regions experiencing rising waste generation and limited landfill capacity [5]. For instance, in Saudi Arabia, the growing urban population and concomitant waste production have heightened the necessity for effective waste management solutions [5]. The incineration process primarily consists of several stages, including waste feed systems, combustion chambers, and exhaust gas handling [43,62,63].

Generally, incinerators operate at temperatures around 850 °C to ensure complete combustion, resulting in CO_2 and water vapor as primary emissions [63,64]. While this technology effectively reduces waste volume and mitigates the infectious properties of medical and hazardous waste, it also necessitates careful management of non-combustible materials (such as metal, glass, etc.), which can form solid residues known as incinerator bottom ash [19]. Two main methods of incineration are commonly applied: mass burn incineration, which processes unsorted waste, and a pre-sorting method that removes recyclable materials before combustion [5,29]. This approach aims to enhance operational efficiency while limiting negative environmental impacts [65]. Table 3 presents a detailed overview of the advantages and disadvantages of incineration technology.

Table 3. Benefits and drawbacks of incineration technology.

Category	Aspect	Description	Ref.
Benefits	Waste Treatment Capacity	Capable of treating almost all types of waste, including mixed MSW, organic, without requiring extensive pre-sorting.	[19,63,64]
	Waste Volume Reduction	The technology achieves a significant reduction in waste mass (70–80%) and volume (80–95%), which greatly reduces landfill demand and addresses land scarcity issues.	[65–68]
	Energy Recovery	Enables energy recovery from non-recyclable waste, producing electricity and heat through steam turbines, thereby substituting fossil fuel-based power generation.	[50,64,69]
	Technological Maturity	A well-established and reliable method with numerous operational plants worldwide.	[63,65,68]
	GHG Reduction	Incineration contributes to GHG mitigation by eliminating CH_4 emissions associated with landfilling and reducing uncontrolled landfill practices.	[50]
	Reuse and Residue	The bottom ash generated (approximately 75–90% of total ash) can be reused as secondary raw material in construction applications such as road base, bridges, and embankments, provided proper treatment and regulation.	[19,64,65]
	Operational Viability	Generally, demands lower capital investments and fewer skilled workers compared to other WtE methods.	[19,63,65,66]

Table 3. *Cont.*

Category	Aspect	Description	Ref.
Drawbacks	Emissions of Air Pollutants	Produces toxic air pollutants, including dioxins, furans, nitrogen oxides, sulfur dioxide, and particulate matter, which cannot be completely eliminated even with advanced pollution control systems.	[41,48,70,71]
	Toxicity of Fly ash	The generation of fly ash containing heavy metals and adsorbed dioxins poses serious environmental and health risks, requiring specialized handling and disposal in controlled landfill facilities.	[41,71–73]
	Residual Waste Volume	Approximately 30% of the original waste remans as tar and ash after incineration, contributing to waste management challenges.	[48,71,74]
	Financial Implications	Involves high upfront and ongoing costs for construction and operational maintenance. The installation and operation of air pollution control devices significantly increase capital and operational costs.	[63,68,70,73]
	Feedstock Requirements	Incineration plants require a minimum waste throughput (50,000 ton/year) and a stable lower calorific value (LCV) ($\geq$7 MJ/kg) to remain economically viable, which limits applicability in regions with high moisture content or variable waste composition.	[75,76]
	Variability in Waste Composition	Differences in waste characteristics can impact the efficiency and effectiveness of the incineration process.	[5,76]
	Need for Skilled Labor	The technology demands well-trained personnel and continuous monitoring, which can be challenging in developing countries.	[41,63]
	Community Acceptance	Local communities may oppose the establishment of incineration facilities due to health and environmental concerns.	[41,68]

The thermal energy generated during incineration can be converted into steam, powering turbines for electricity generation [55]. Generally, the energy recovery efficiency of incineration systems ranges from 20% to 30%, contingent upon various operational factors [5,19]. Advanced processing techniques, such as pre-treatment of solid waste, can improve energy efficiency by optimizing the calorific value of the waste materials [65,75]. Despite the benefits of waste volume reduction and the diminishing environmental hazards associated with landfills, incineration raises concerns about pollutant emissions, necessitating effective management strategies to control the release of harmful substances and comply with environmental regulations [19]. As highlighted in Saudi Arabia's Vision 2030, the transition to incineration is viewed as a strategic approach to curbing GHG emissions and enhancing waste management practices [77]. Investment in incineration technology offers promising opportunities from both economic and environmental standpoints.

The Saudi government, acknowledging the pressing need for efficient waste management, allocated SAR 54 billion for municipal services in 2017, reinforcing its commitment to sustainable practices [31]. Additionally, the implementation of incineration aligns with the objectives of Vision 2030, which aims to reduce GHG emissions and promote cleaner energy production. Ongoing initiatives focus on refining incineration practices and exploring carbon capture technologies to address environmental concerns. Table 4 provides the studies that have evaluated the incineration process within Saudi Arabia.

Table 4. Overview of incineration technology for MSW in different regions of KSA.

City	Waste Type	Waste Generation, t/day	Operating Conditions	Energy Recovery and Performance	Environmental Impact	Ref.
Dammam	MSW	-	Three Scenarios: 1. MRF with composition. 2. Landfilling. 3. Incineration	About 1.91 × 10^9 kWh/year electricity from incineration. -Reduces fossil fuel usage by 1.12 × 10^6 barrels/years.	-Scenario 1: −2,142,618 tCO_2-eq/year. -Scenario 2: +0.265 tCO_2-eq/t MSW. -Scenario 3: GHG reduction of −287,873 tCO_2-eq/year.	[50]
Eastern Province, KSA	Mixed MSW	8.21 ton/day (3000 t/year).	Incineration, LCV ≥ 6–7 MJ/kg. Implementation of the 3R system in a residential camp (11,000 people).	254 MW electricity from complete incineration. -38 MW (with recycling) -Sufficient for 25,951 households.	-Significant reduction in GHG emissions. -Lowers CH_4 and global warming potential (GWP) compared to landfilling. -Reduced waste generation from 5625 tons to 3000 tons/year.	[62]
Jeddah	Mixed MSW: For incineration: MSW. For incineration with recycling: non-recyclable waste after removed	4682 t/day (2012)	Two Scenarios: 1. Incineration. 2. Incineration with recycling.	-Estimated electricity generation: 180 MW for Incineration. -11.25 MW for Incineration with recycling.	-Reduces landfill reliance and mitigates CH_4 emissions from landfills.	[65]
Makkah	Mixed MSW: For incineration: MSW. For incineration with recycling: non-recyclable waste after removed	2858 t/day (2012)	Two Scenarios: 1. Incineration. 2. Incineration with recycling.	-87 MW for Incineration. -5.45 MW for Incineration with recycling.	-Reduces landfill reliance and mitigates CH_4 emissions from landfills.	[65]
Madinah	Mixed MSW: For incineration: MSW For incineration with recycling: non-recyclable waste after removed	2165 t/day (2012)	Two Scenarios: 1. Incineration. 2. Incineration with recycling.	-61.3 MW for Incineration. -3.84 MW for Incineration with recycling.	-Reduces landfill reliance and mitigates CH_4 emissions from landfills.	[65]
Eastern Province (Dammam, Khobar, Dhahran, Sihat, and Qatif)	MSW	Estimated annual MSW generation in 2010 was 3 million tons, projected to rise to 7 million tons by 2035.	Incineration	Potential to generate approx. 272 MW of electricity by 2035.	-Significant reduction in waste and electricity generation potential. -Supports future carbon credit and LCA benefits.	[43]

Table 4. *Cont.*

City	Waste Type	Waste Generation, t/day	Operating Conditions	Energy Recovery and Performance	Environmental Impact	Ref.
KSA	MSW	The study emphasizes the increase in MSW generation leading up to 2032.	Incineration	Energy demand reduction of 9.9 million barrels of crude oil.	-GHG emission reduction of about 4.8 million metric tons of carbon equivalent per year (MTCE/year). -Landfill area saving of 90%.	[78]
KSA	MSW	-	Incineration	2073 MW.	-Significant contribution to electricity supply, potential for reduced landfilling.	[5]
KSA	MSW	-	-	Contributes up to 2.3% to energy demand.	-Prevents landfill overuse, generates energy from waste.	[55]
Riyadh	MSW	-	Incineration with recycling	Up to 3.17% of household electricity demand, 1.51% of total demand.	-GHG emissions reduced by 55%.	[31]
Riyadh	MSW	-	Incineration with maximized recycling	Higher potential for energy recovery.	-GHG emissions reduced by 58%.	[31]
Riyadh	Mixed MSW	-Estimated 60,575 t/day (22.11 million t/year).	Incineration (used for energy recovery process)	-Electricity generation of 927 MW in 2015 and 1692 MW in 2032. Energy content: 10,159.2 kJ/kg.	-Significant landfill impacts. -Potential reduction in fossil fuel reliance.	[2]
Riyadh	Mixed MSW	-Estimated 60,575 t/day (22.11 million t/year).	Incineration with recycling	-Electricity generation of 796 MW in 2015 and 1461 MW in 2032. Energy content: 3225.4 kJ/kg.	-Reduced energy capacity due to recycling.	[2]
KSA	MSW	-Estimated 60,575 t/day (22.11 mt/year)	Incineration plants	11.13 TWh/year of electricity generation	-GHG emissions: 4.36 million tons CO_2 eq/year.	[10]

Research on incineration-based WtE systems in Saudi Arabia demonstrates a significant methodological, even though the studies differ in their geographic focus, waste characteristics, and analytical scope. Collectively, these investigations confirm that incineration is a technically viable and environmentally advantageous approach for managing MSW, especially when compared to traditional landfilling practices.

At the local and regional levels, studies conducted in Dammam [50] and the Eastern Province [43,62] underscore the effectiveness of incineration under various operational frameworks. Scenario-based analyses have compared material recovery facilities (MRF), landfilling, and incineration, consistently revealing that incineration provides superior energy recovery and GHG mitigation [50]. For instance, in Dammam, incineration is estimated to generate approximately 1.91×10^9 kWh annually, which corresponds to a reduction in fossil fuel consumption by 1.12×10^6 barrels per year, resulting in a net negative carbon footprint [50]. Complementing these findings, regional studies in the Eastern Province indicate that the complete incineration of mixed MSW could yield up to 254 MW of electricity, sufficient to supply nearly 26,000 households [62], while significantly diminishing CH_4 emissions compared to landfilling [62].

Further supporting the robustness of incineration as a WtE solution are studies from the Western Province, particularly in cities like Jeddah, Makkah, and Madinah [65]. Research by Ouda et al. [65] has shown that incineration can achieve the highest electricity outputs, ranging from 61.3 MW in Madinah to 180 MW in Jeddah. When recycling is incorporated prior to incineration, although there is a notable decrease in energy output, this is offset by enhanced resource recovery and lowered environmental impacts [65]. The objectives of maximizing energy recovery and environmental performance are not always aligned but can be effectively balanced through integrated system designs.

On a national scale, several studies extend these regional insights by connecting trends in MSW generation to future energy demands [5]. While this contribution represents a modest fraction of total national electricity demand, it plays a strategically crucial role in reducing landfill reliance, conserving land area, and decreasing fossil fuel consumption. Notably, scenarios that include recycling yield lower power outputs but provide significantly greater environmental benefits, including crude oil savings of up to 55.6 million barrels annually and GHG emission reductions exceeding 15.2 million metric tons of carbon equivalent each year [78].

Life cycle assessment (LCA) studies conducted in Riyadh further substantiate these conclusions by evaluating the broader environmental impacts of incineration [31]. These studies demonstrate that the combination of incineration and recycling can reduce GHG emissions by 55% to 58% compared to landfill-dominated systems, while also contributing up to 3.17% of household electricity demand [31]. Such findings reinforce the importance of evaluating WtE technologies not only based on their energy yield but also through comprehensive environmental performance metrics.

Overall, regional analyses establish the technical feasibility of incineration, national-scale projections highlight its strategic significance, and LCA studies confirm its environmental sustainability. Together, these works support the assertion that incineration, especially when integrated with recycling and other waste management practices, represents a cornerstone technology for sustainable MSW management and resource recovery in Saudi Arabia.

4.1.2. Plasma Arc Gasification

Plasma arc gasification represents a cutting-edge thermochemical technology aimed at converting carbonaceous waste into valuable energy products [79]. This process operates at extremely high temperatures generated by an electrically powered plasma torch, contrasting

with traditional gasification methods [29,79]. Unlike these conventional approaches, plasma arc gasification functions under oxygen-deficient or partially oxidizing conditions [80,81]. This environment facilitates complete molecular dissociation of organic materials rather than merely promoting partial combustion. Consequently, MSW and intricate waste streams are efficiently transformed into synthesis gas (syngas) and an inert vitrified slag [80,81].

Plasma is often referred to as the fourth state of matter and consists of highly ionized gases resulting from electrical discharge at temperatures typically between 2000 and 5000 °C [29,48,79]. Under these harsh thermal conditions, the chemical bonds of organic materials are fully broken down, enabling the conversion of complex hydrocarbons into simpler gaseous molecules, primarily H_2 and CO [82]. Simultaneously, the inorganic portion of the waste melts and solidifies into a glass-like, non-leachable slag upon cooling, which is chemically stable and environmentally friendly [82,83].

The plasma arc gasification system is fundamentally centered around the plasma torch, which facilitates the conversion of electrical energy into high-intensity thermal energy [56]. Plasma torches can operate in either transferred or non-transferred arc configurations [56]. In transferred arc systems, the arc forms directly between the torch electrode and the waste material, achieving high energy transfer efficiency [48,56,79]. In contrast, non-transferred arc systems confine the arc within the torch body, relying on the generated plasma jet to transfer heat indirectly to the waste. Both configurations ensure rapid heat transfer, elevated reaction rates, and nearly complete waste destruction [56].

Plasma arc gasification encompasses several sequential stages: waste pre-treatment (including shredding or size reduction), feeding into the plasma reactor, high-temperature thermal decomposition and gasification, syngas cooling and purification, followed by final energy recovery [46,79]. The performance of the process is significantly influenced by various operational parameters, including reactor temperature, residence time, pressure, and external electrical energy input [82,84]. By meticulously managing these parameters, the composition and heating value of syngas, especially the hydrogen-to-carbon monoxide (H_2/CO) ratio, can be optimized for diverse downstream applications such as electricity generation, heat recovery, H_2 production, or synthetic fuel synthesis [82,84]. Table 5 presents a detailed overview of the advantages and disadvantages of plasma arc gasification technology.

Table 5. Benefits and drawbacks of plasma arc gasification technology.

Category	Aspect	Description	Ref.
Benefits	Waste Treatment Capacity	Efficiency processes various waste types, including MSW, industrial, medical, and hazardous waste, with minimal pre-treatment.	[80,82,85,86]
	Waste Volume Reduction	Achieves significant reductions in waste (up to 99%) and weight (up to 85%) through gasification and vitrification processes.	[80,81]
	Energy Recovery	Converts waste into high-quality synthetic gas (syngas) for electricity generation, heating, and synthesis of fuels or chemicals.	[84,87]
	GHG Reduction	Can reducing GHG emissions by diverting waste from landfills (major source of CH_4) and by displacing fossil fuels with syngas.	[29]
	Reuse and Residue	Produces vitrified slag, an inert material that can be used as a construction aggregate. Potential to recover valuable products (metals) from slag.	[58,80]
	Operational Viability	Potential for high rates of return and profit margins; can be integrated with existing waste management systems.	[46,58,80]

Table 5. *Cont.*

Category	Aspect	Description	Ref.
Drawbacks	Emissions of Air Pollutants	Under ideal conditions, emissions can be very low, and the process can avoid producing dioxins and furans common in incinerators. However, important operation can still lead to the release of CO_2 and other pollutants.	[48,87]
	Toxicity of Fly ash	Minimize toxic emissions, but nanoparticles presence in syngas can be a concern; vitrified slag is less toxic than conventional incineration ash.	[46]
	Residual Waste Volume	Generates 10–15% residual based on the original waste volume, despite significant volume reduction.	[82]
	Financial Implications	High capital investment and operating costs due to electricity consumption and maintenance.	[46,80]
	Feedstock Requirements	Requires shredding waste (size < 100 mm) for optimal gasification efficiency, best performance with high-calorific pre-processed materials.	[88]
	Variability in Waste Composition	Syngas yield can be impacted by fluctuations in waste composition, especially seasonally.	[48,89]
	Skilled Labor Requirement	The operation and maintenance require trained personnel due to the complexity of the technology.	[82]

One of the primary advantages of plasma arc gasification is its remarkable feedstock flexibility. The technology is capable of processing various waste materials, including MSW, plastics [46,48], hazardous and medical wastes [79,85], RDF [49], biomass [56], tires [82], and automotive shredder residue (ASR) [47], with minimal pre-treatment required [79]. Unlike traditional thermal processes, high moisture content does not significantly impede system performance due to the extreme operating temperatures, making plasma gasification especially adept at handling heterogeneous and contaminated waste streams [19,80].

The primary product of plasma arc gasification is syngas, which retains a substantial portion of the original chemical energy present in the waste [46,48]. This syngas can be utilized directly in gas engines or turbines for electricity and heat generation or further refined into liquid fuels and chemical products such as methanol and H_2 [46,48]. Additionally, the inorganic fraction is converted into vitrified slag, which is chemically inert, non-hazardous, and suitable for reuse as construction aggregate, enabling a reduction in landfill waste volume by up to 99% [80,81]. From an environmental perspective, plasma arc gasification offers considerable advantages over landfill disposal and conventional incineration. The process results in minimal CH_4 emissions, significantly reduces GHG emissions, and effectively destroys toxic organic compounds at the atomic level [82]. The high-temperature plasma conditions also promote the reduction of hazardous pollutants such as mercury, particularly in plastic-rich waste streams, thereby contributing to the production of cleaner alternative fuels [87].

Nevertheless, plasma arc gasification is not without limitations, primarily concerning economic and operational factors. The technology demands substantial capital investment and operational costs due to the significant electrical power requirements of plasma torches, sophisticated control systems, and the need for specialized labor [84]. Consequently, economic feasibility is highly sensitive to electricity pricing, plant scale, and energy recovery efficiency. As such, this technology has predominantly been deployed in areas with limited landfill capacity and stringent environmental regulations, such as Japan, while remaining largely at the pilot or demonstration stage in other regions [86,87].

Plasma arc gasification has been the focus of three significant studies specifically conducted in Makkah, Saudi Arabia, offering an in-depth examination of the technology within the context of urban waste management and the unique challenges posed by pilgrimage-related waste [48]. These investigations collectively explored the technical feasibility, environmental impact, and economic viability of the technology, especially in light of the rapidly escalating waste generation in the region [48]. Galaly et al. [48] highlighted the growing challenges of waste disposal in Makkah, noting an increase in landfill waste from 168,000 Mg in 1994 to 297,000 Mg by 2022, alongside rising costs associated with environmental pollution. Their research indicated that using air plasma torches for plasma arc gasification of plastic waste could yield approximately 317,000 tons of pyrolysis oil, translating to an energy output of 12.55×10^9 MJ and achieving an efficiency rate of 81%. Economically, this system demonstrated a return on investment of 80%, a payback period of 1.2 years, and a gross profit margin of 129%, all while generating near-zero harmful emissions [48]. Building on these findings, Galaly et al. [46] investigated a larger-scale plasma gasification facility designed to process 200 tons/day of increasing plastic waste in Makkah, which expanded from 224,000 tons in 1994 to 400,000 tons in 2022. This study outlined the plasma treatment methodology, which included pre-treatment stages, high-temperature conversion into syngas, pyrolysis oil, and vitrified slag within a temperature range of 1500–5000 °C, followed by purification and energy recovery processes. The anticipated outputs comprised 317,000 tons of pyrolysis oil, 270,000 tons of diesel-equivalent fuel, and approximately 2.96 million MWh of electricity, all underscoring a commitment to zero emissions and alignment with sustainable development objectives [46].

Moreover, Galaly and Oost [82] explored the Plasma Treatment Project (PTP) in Makkah during peak pilgrimage seasons, when annual waste generation can reach approximately 750,000 tons. Their analysis revealed that a 100 tons per day plasma system could produce up to 23.8 MW of electricity, generating annual profits of about 3.27 million EUR. The study affirmed the capability of plasma arc gasification to process a diverse range of waste streams, while ensuring environmental safety and operational dependability [82]. Table 6 provides a summary of the key characteristics and findings from the plasma arc gasification studies conducted in Makkah, Saudi Arabia.

Table 6. Overview of plasma gasification technology for MSW in Makkah.

City	Waste Type	Waste Generation, ton/day	Operating Conditions	Energy Recovery and Performance	Environmental Impact	Ref.
Makkah	Plastic Waste (especially Zam-Zam Plastic Waste (Zz-PW)	-	-Air plasma torches operating at a flow rate of 10–30 g/s, power of 125 kW, plasma temp. between 15,000–19,000 K, and vapor velocities of 1677.3–2763.2 m/s.	-3.17×10^5 tons of pyrolysis oil (2022), equivalent to 12.55×10^9 MJ, with an efficiency of 81%.	-Emission costs increased from 4 million (1994) to 7 million (2022). -Gas emissions from Zz. PW in landfills rose from 128,000 Mg to 227,000 Mg over the same period.	[48]
Makkah	Plastic Waste	224,000 (1994)–400,000 (2022) t/year	Plasma gasification reactor, 1500–5000 °C, air plasma torch, 125 kW. Two torches, maximum consumption of air = 28 mg/s.	-Pyrolysis oil: 317,000 ton/year, Diesel oil: 270,000 ton/year, electricity: 2.96×10^6 MW.h.	-Zero emissions from plasma reactor, reduces landfill pollution, high energy recovery.	[46]

Table 6. *Cont.*

City	Waste Type	Waste Generation, ton/day	Operating Conditions	Energy Recovery and Performance	Environmental Impact	Ref.
Makkah	Mixed MSW (Slaughter-house waste, car tires)	-During normal day: 1800–2000 t/day. -During Ramadan: 3000 t/day. -During pilgrimage season (Hajj): up to 4500 t/day.	Thermal plasma reactor, plasma temperature (1500–5000 °C), limited oxygen, capacity: 100 t/day per reactor.	-23.8 MW electricity, 3.27 million EUR profit/year. -0.447 MWh/ton energy consumption, syngas used for power generation.	-Low emissions, reusable slag, reduction pollution, safe disposal, reduction in hazardous materials, destruction of Persistent organic pollutants (POPs), and inert slag (10–15% residue).	[82]

4.1.3. Gasification

Gasification is an established thermochemical conversion technology applied in WtE systems. It transforms carbon-rich feedstocks, such as MSW, RDF, biomass, coal, and industrial residues, into a combustible gas mixture known as syngas under conditions of limited oxygen availability [68,90,91]. Unlike direct combustion or incineration, which involves complete oxidation, gasification uses a controlled amount of an oxidizing agent (air, oxygen, or steam) to partially oxidize the feedstock [92]. This process breaks down complex organic molecules into simpler gases, mainly H_2, CO, along with minor amounts of CH_4, CO_2, higher hydrocarbons (tar), and char [92–94].

The syngas produced is a versatile energy carrier. It can be directly combusted for electricity or heat generation, utilized in combined-cycle power plants, reciprocating engines, or fuel cells, or serve as a feedstock for chemical production, including methanol, ammonia, urea, or ethanol [91,95]. Gasification is considered an environmentally friendly and efficient alternative to fossil fuel combustion, as it facilitates energy recovery from low-value residues while minimizing harmful emissions [96,97].

The gasification process involves several integrated stages. Pre-treatment ensures stable and efficient operation by sorting, shredding, and drying the feedstock to maintain a uniform particle size and moisture content below 15% [91,97]. The pre-treated feedstock is then fed into a gasifier reactor, where high temperatures, typically around 700–850 °C for biomass and 800 °C for conventional gasifiers, facilitate pyrolysis, char gasification, and reforming reactions to generate syngas [44,90]. Key parameters such as gasification temperature, steam-to-biomass ratio, char split ratio, particle size of the feedstock, and type of gasifying agent greatly influence the composition, yield, and heating value of the syngas [93].

Gasification offers several advantages over traditional WtE methods. Operating under low-oxygen conditions reduces the production of hazardous by-products, such as dioxins and furans, which are often generated in incineration processes [63]. This process is also energy-efficient, consumes less oxygen, generates smaller volumes of gas, and simplifies pollutant capture due to higher contaminant partial pressures in the gas phase [63]. Additionally, gasification significantly decreases waste volume, typically reducing it by around 90% and leaving only 8–12% residual ash, which is less than that from conventional incineration [91,98]. The technology's adaptability allows it to process heterogeneous waste streams, including MSW, RDF, biomass, coal, sludge, black liquor, PVC, tires, and ASR, provided that pre-processing removes inorganic contaminants [91,97,99,100]. This versatility enhances its appeal for urban WtE applications and supports circular economy strategies by recovering energy from otherwise wasted materials [91,99].

Nevertheless, gasification also presents challenges. The syngas produced may contain tars, alkaline compounds, halogens, and heavy metals, which can impact operational stability and pose environmental risks if not adequately treated [98,101]. For instance, alkalis in fluidized-bed gasifiers can lead to agglomeration, tars can harm filtration and catalytic systems, halogens may cause corrosion, and uncontrolled heavy metals can accumulate [95]. Additionally, setting up gasification plants typically demands a significant capital investment, along with operational complexity and a skilled workforce [14,18,95,96]. Despite these challenges, advancements in dual fluidized-bed (DFB) gasifiers, gas cleaning technologies, and process integration are enhancing operational efficiency, syngas quality, and environmental performance [19,102,103]. Table 7 summarizes the primary benefits and drawbacks of the gasification process.

Table 7. Benefits and drawbacks of gasification technology.

Category	Aspect	Description	Ref.
Benefits	Waste Treatment Capacity	Gasification can process heterogeneous MSW streams, including mixed organic and plastic fractions, making it suitable for urban waste with variable composition. Utilizes abundant agricultural residue, reducing waste disposal requirement. High efficiency in treating MSW.	[57,65,90]
	Waste Volume Reduction	The conversion of solid waste into syngas and limited solid residues significantly reduces the volume requiring landfilling. Reduces waste volume by 90%.	[63,90,98]
	Energy Recovery Potential	Syngas can be used flexibly for electricity generation, heat recovery, or upgrading into synthetic fuels and chemicals. Produces syngas (H_2 + CO + CH_4) usable for electricity, heat, and chemical production.	[48,57,104]
	Environmental Performance	Oxygen-deficient operation limits uncontrolled combustion and can reduce emissions compared to direct incineration when appropriate gas cleaning is applied. Reduces CH_4 emissions compared to landfilling, lower flue gas and pollutants than incineration.	[57,68,90]
	Circular Economy Compatibility	Gasification supports circular economy concepts by recovering energy and enabling potential valorization of by-products. Syngas can be used as feedstock for value-added chemicals.	[19,99]
	Urban Applicability	Suitable for cities facing landfill scarcity and continuous waste generation, especially in rapidly growing urban areas. Suitable for heterogeneous waste stream in urban environments.	[29,57]

Table 7. *Cont.*

Category	Aspect	Description	Ref.
Drawbacks	Air Pollutant Control Requirements	Syngas cleaning is essential to remove particulates, tar, and trace contaminants, increasing system complexity. Syngas may contain tars, alkalis, halogens, and heavy metals, requires gas cleaning.	[68,90]
	Residual Waste Generation	Solid residues and tar are still produced and require regulated handling and disposal. Produces 8–12% ash that still requires disposal or reuse.	[63,90,98]
	High Capital Investment	Gasification plants require significant initial investment in reactors, gas cleaning system, and energy recovery units.	[29]
	Operational Complexity	Stable operation depends on precise control of temperature, equivalence ratio, and feedstock properties.	[90]
	Sensitivity to Feedstock Variability	Changes in waste composition and moisture content can affect syngas quality and process efficiency. Feedstock composition, moisture, and particle size affect gasification efficiency.	[19,57]
	Skilled Labor Requirement	Operation and maintenance require trained personnel and advanced control systems. Technicians needed for operation, maintenance, and gas cleaning.	[29]

In Saudi Arabia, gasification has emerged as a versatile WtE technology well-suited to addressing the diverse challenges of waste management, from urban MSW to agricultural residues and microalgae. The research conducted by Rehan et al. [25], Ali et al. [57], Findley et al. [105], and Al-Rabiah et al. [106] collectively illustrate the practical applications of this thermochemical conversion technology across various contexts within the country. These studies highlight gasification's adaptability, environmental benefits, and potential for energy recovery. The type of waste processed directly influences the by-products generated. As shown in Table 8, which provides an overview of gasification for MSW in Saudi Arabia, MSW and date palm fronds (DPF) primarily yield combustible syngas with minimal residual ash, while camp waste generates biochar that is beneficial for soil enhancement. In contrast, microalgae conversion produces both syngas and methanol, alongside manageable residuals. These variations underline how the characteristics of different feedstocks dictate the overall outputs from the gasification process.

Rehan et al. [25] focus their investigation on a simulated 50 t/day gasification plant targeting urban MSW in Jeddah. This study underscores the environmental advantages and economic feasibility of gasification at the city level, revealing a significant reduction of 100 kg of CO_2-eq emissions for every ton of waste processed. This work emphasizes traditional WtE applications, particularly regarding the production of syngas for electricity generation, which aligns with broader efforts to address climate change and enhance energy security in urban settings. In parallel, Ali et al. [57] explore the potential of agricultural residues, specifically DPF, in a downdraft gasifier. Although this study operates on a smaller scale, it provides critical insights into the optimization of gasification parameters, revealing that temperature plays a role in determining syngas composition. By maximizing H_2 and CO output, this study highlights how the choice of feedstock influences not only process design but also syngas quality for chemical applications. The findings from Ali

et al. complement those of Rehan et al. by demonstrating that different feedstock types can be effectively utilized to produce high-value energy products, reinforcing the adaptability of gasification technology across diverse contexts.

Table 8. Overview of gasification technology for MSW in KSA.

City	Waste Type	Waste Generation, ton/day	Operating Conditions	Energy Recovery and Performance	Environmental Impact	Ref.
Jaddah	MSW	5000 t/day (city-wide), 50 t/day (modeled)	Fluidized bed gasification, simulation-based, gate-to-gate boundary	274.3 kWh/ton electricity, 4.94 GWh/year	Reduced fossil depletion and PM formation, -Processed of 100 kg CO_2 eq. per ton.	[25]
KSA	DPF (Organic waste)	-	Downdraft air gasification. DPF mass flowrate: 0.6 kg/h. Temperature: 900 °C. air flow: 1 I/min. Particle size: 6 mm. -Lab/Small-scale.	Syngas production: (H_2: 15.85 Vol%, CO: 14.65 Vol%., CH_4: 8.09 Vol%., CO_2: 8.85 Vol%.	Reduced CO_2 emissions compared to fossil fuels. Syngas can be utilized for energy or chemical production.	[57]
Remote workover camp, KSA	Mixed organic waste (camp garbage and kitchen waste)	-	Batch gasification (20–40 kg/h), temperature > 600 °C, modular and transportable gasifier, syngas internally recycled to sustain operation, rapid quenching <200 °C.	Syngas generated and combusted on-site to maintain autothermal operation >95% waste volume reduction achieved.	Significant reduction in waste volume, suppression of dioxins and furans due to rapid quenching, non-toxic biochar residue, and sterilization of inorganic waste.	[105]
Western Coast of KSA (Red Sea Region)	Microalgae biomass: - Nannochloropsis oculate. - Dunaliella salina	-	-DFB gasifier, temperature: 700–850 °C, steam-to-biomass ratio optimized (0.4–0.6), char spilt < 75%, Aspen plus simulation.	-Coproduction of 290 metric ton/day methanol and 38 MW of electricity, syngas rich in H_2 and CO.	-Reduced solid residues, potential carbon neutrality, CO_2 stream reusable for algae cultivation.	[106]

The flexibility of gasification is further exemplified in the work of Findley et al. [105], who introduce a modular, transportable gasifier designed for use in remote locations. This study diverges from the urban and agricultural focuses of Rehan et al. [25] and Ali et al. [57] by emphasizing operational flexibility and waste volume reduction. By processing organic camp waste and kitchen scraps in small batches, this system achieves over 95% waste volume reduction, recovering energy through internal syngas combustion, and managing by-products safely through the production of non-toxic biochar suitable for soil enhancement, thereby contributing to effective waste management in remote settings. This adaptability shows that gasification can effectively operate in decentralized or temporary settings, highlighting its practicality across various Saudi contexts. In a more industrial context, Al-Rabiah et al. investigate the use of microalgae biomass in a DFB gasifier for the concurrent production of methanol and electricity [106]. They utilize a DFB gasifier to process microalgae from the Red Sea, achieving a biomass conversion efficiency of 45.7% to produce methanol while generating 38 MW of electricity. This study illustrates how gasification can optimize value extraction from specialized feedstocks. This research extends the scope of previous studies by integrating chemical production with energy generation, illustrating the multifaceted benefits of gasification in an industrial setting.

Together, these studies emphasize gasification's strengths in Saudi Arabia, including its adaptability to various feedstocks, such as MSW, DPF, microalgae, and camp waste, significant energy recovery potential, and substantial waste volume reduction. These attributes align closely with environmental and circular economy objectives. Critical operational parameters, such as gasifier temperature, feedstock preparation, and syngas management, consistently emerge as essential for maximizing process efficiency and product quality, regardless of whether the goal is electricity generation, H_2 production, or methanol synthesis. Gasification in Saudi Arabia represents a flexible, scalable, and environmentally beneficial WtE technology capable of transforming diverse organic materials into valuable energy and chemical products. This approach contributes to reducing landfill dependency and aligns with the renewable energy goals outlined in Vision 2030.

4.1.4. Pyrolysis

Pyrolysis is an advanced WtE thermochemical conversion method that thermally decomposes carbonaceous materials in an oxygen-free or limited oxygen environment. This process typically occurs at temperatures between 300 and 1000 °C, depending on the specific operational setup and target product distribution [45,107–109]. Through this thermal treatment, MSW and other waste types are transformed into three primary products: solid char, liquid pyrolysis oil (bio-oil), and gaseous products known as syngas [45,110–113].

The yield and composition of pyrolysis products are significantly affected by various operational factors, including feedstock type and composition, particle size, heating rate, reaction temperature, vapor residence time, and pressure conditions [114,115]. Lower temperatures tend to favor liquid product formation, while higher temperatures promote reactions such as volatile cracking and decarboxylation, leading to increased syngas output with reduced yields of bio-oil and char [115–117]. Typically, syngas from pyrolysis contains CO, H_2, CO_2, and CH_4, while the liquid product is composed of complex oxygenated hydrocarbons, and the solid product is mainly carbon-rich char [45,111,112].

Pyrolysis offers considerable operational flexibility, allowing adjustments to process parameters to optimize yields based on energy or material recovery goals [110]. The pyrolytic liquid can be used directly in boilers, furnaces, and engines with minimal upgrading, or can be refined into transportation fuels and chemical feedstocks [118,119]. The char generated is valuable due to its high heating value and can be utilized for power generation, soil enhancement, carbon sequestration, or as a precursor for materials like activated carbon and biochar [120,121]. The production of char from pyrolysis has a long history in the creation of coke and charcoal from biomass and coal, indicating its technological maturity [121].

Pyrolysis can be classified into three main types based on heating rate, temperature, and residence time: slow, fast, and flash pyrolysis. Slow pyrolysis operates at heating rates of 0.1–2 °C/s and around 550 °C, which encourages char and tar production. Fast pyrolysis uses moderate temperatures (586–977 °C) and short residence times (0.5–10 s) to yield high amounts of bio-oil. Flash pyrolysis, which occurs at very high temperatures (777–1027 °C) with rapid heating rates, primarily produces gas-rich products suitable for alcohol and gasoline production [19]. Fast pyrolysis is the most commonly utilized for WtE applications due to the fuel-like characteristics of its products and their compatibility with existing energy infrastructures [19].

However, applying pyrolysis to MSW involves significant challenges because of the heterogeneous nature of municipal waste [122]. The yield and quality of products from MSW pyrolysis can vary greatly depending on feedstock composition, with gas yields often falling below 1 Nm^3/kg MSW, equating to a calorific value of about 15 MJ/Nm^3 [123]. Additionally, the liquids obtained from mixed MSW typically contain high water content

and complex chemical compounds, requiring advanced treatment prior to disposal or reuse, which compromises overall energy and material recovery efficiency [123]. Although MSW-derived char holds substantial energy potential, contamination from heavy metals and toxic organic pollutants necessitates careful handling and treatment before use [120]. Table 9 summarizes the primary benefits and drawbacks of the pyrolysis process.

Table 9. Benefits and drawbacks of pyrolysis technology.

Category	Aspect	Description	Ref.
Benefits	Waste Treatment Capacity	Pyrolysis is highly effective in processing plastics and biomass, particularly municipal plastic waste (MPW). The thermal degradation technique operates in the absence of oxygen, allowing for the efficient conversion of long-chain polymer molecules into simpler compounds. Fast pyrolysis can transform biomass into valuable products such as bio-oil, char, and syngas at temperatures exceeding 400 °C, achieving a substantial reduction in MSW volumes, which can range from 50–90%.	[107,124–127]
	Energy Recovery Potential	The pyrolysis process generates a variety of energy-rich outputs, including fuel oil, combustible syngas, tar, and char. These products process high heating and calorific values, making them suitable for a range of applications, such as electricity generation, industrial refining, and heating systems. Pyrolysis allows for the recovery of up to 80% of the energy from waste, producing oils and gases that can be utilized in boilers and diesel engines without further processing.	[118,120,124,128,129]
	Environmental Performance	By reducing the reliance on landfills, pyrolysis minimizes GHG emissions. The char produced during the process can be utilized for pollution remediation through ion exchange and precipitation. Additionally, the absence of oxygen during pyrolysis limits the creation of harmful by-products such as furans and dioxins, resulting in relatively low pollution compared to traditional waste management technologies.	[19,33,130]
	Circular Economy Compatibility	The outputs of pyrolysis, including char and bio-oil, can be repurposed as fuels or feedstock for further processing, such as gasification and activated carbon production. These products support material recovery and contribute to a circular economy by allowing refinements that enable their use in various applications, including chemicals and adhesives.	[19,124,131]
	Urban Applicability	Pyrolysis plants require significantly less land compared to conventional waste disposal methods like RDF or plasma arc systems, making them suitable for urban and industrial contexts. This also means that such facilities can be integrated into existing infrastructure with moderate labor requirements.	[16,19,33,132]

Table 9. *Cont.*

Category	Aspect	Description	Ref.
Drawbacks	Air Pollutant Control Requirements	The pyrolysis process products air emissions that include corrosive tars, acidic gases, and toxic residues, which necessitate robust cleaning and emission control systems to mitigate environmental impacts.	[19,33,63]
	Residual Waste Generation	Solid by-products such as char and tar are produced during pyrolysis and require proper management and disposal. Other by-products may include coke, toxic residues, and pyrolytic water, adding to the complexity of waste management.	[63,120,124]
	High Capital Investment	The initial investment for setting up a pyrolysis facility is considerable. This includes costs associated with the sorting and pretreatment of MSW and the segregation of inert materials, potentially deterring new investments.	[33,133]
	Operational Complexity	Operating pyrolysis systems involves careful control of thermochemical processes, including temperature and residence time, to optimize product yields. Challenges such as tarring, blockages, corrosion of components, and the need for airtight reactors can complicate operations.	[118,134–136]
	Sensitivity to Feedstock Variability	Pyrolysis is sensitive to the quality and composition of feedstock, as contamination or mixed plastics can reduce yield and product quality. Effective sorting and pretreatment are crucial. Moreover, the process is vulnerable to accidental air intrusion, which can disrupt operations or lead to hazardous reactions.	[87,125,133,137]
	Skilled Labor Requirement	The complexity of the pyrolysis process necessitates a workforce with specialized training in sorting, pretreatment, and process control, highlighting the need for skilled operators to manage the system effectively.	[16,33,133]

To improve process efficiency and power generation capacity, pyrolysis systems necessitate consistent and well-prepared feedstock. Typical feedstocks include MSW, RDF, plastics, biomass, sewage sludge, tires, coal, ASR, and polymer-rich wastes [45,115]. Preprocessing tasks such as sorting, shredding, and drying are vital for removing inorganic materials, reducing particle size below 50 mm, and lowering moisture content to approximately 20%, thus ensuring stable reactor operation and enhanced energy recovery [19]. Sorted plastic waste, in particular, is better suited for oil production than heterogeneous MSW [123,138,139]. The overall efficiency of pyrolysis is comparable to gasification, with both technologies able to treat a wide range of municipal wastes. However, pyrolysis is less technologically mature than traditional incineration and AD methods [140]. Nevertheless, the syngas and pyrolysis oil produced can be combusted to generate thermal energy, steam, and electricity, making pyrolysis a promising option for integrated energy recovery and resource valorization in sustainable waste management systems [19,115,138,139].

Pyrolysis has increasingly been recognized as a versatile WtE technology in Saudi Arabia, capable of converting various waste streams into valuable fuels and materials, aligning with national objectives aimed at energy diversification and environmental pro-

tection. At the national level, Nizami et al. [33] conducted an evaluation of different WtE technologies and identified pyrolysis as especially suitable for plastic waste, estimating a theoretical electricity generation potential of approximately 1.03 TWh per year. Table 10 presents a summary of several studies on the pyrolysis of MSW in Saudi Arabia. While these national estimates are promising, they remain largely conceptual, underscoring the need for localized, site-specific investigations.

Table 10. Overview of pyrolysis technology for MSW in KSA.

City	Waste Type	Waste Generation, ton/day	Operating Conditions	Energy Recovery and Performance	Environmental Impact	Ref.
KSA	Plastic waste (17.4%)	Estimated 2.7 million tons yearly (7400 ton/day).	-Seasonal spikes during Ramadan and Hajj.	Estimated electricity generation potential: 1.03 TWh annually if all plastic waste is utilized. Pyrolysis process efficiency: 17%	Converts waste into valuable products (fuel oil, char, gas, and coal), reduces mitigates pollution.	[33]
Makkah	Plastic waste (plastic bottles, water cups, food plates, and shopping bags) (23% of MSW)	0.263 million tons yearly (2016). 0.516 million tons yearly (2040 projected).	-Generated by locals, pilgrims, and during Ramadan. -Clogging and slow degradation.	Potential to generate 87.91 MW electricity in 2016 (0.21-million-ton liquid fuel), projected to rise to 172.8 MW by 2040 (0.412-million-ton liquid fuel). Pyrolysis yield efficiency of 80%, liquid fuel has high heating of 40 MJ/kg.	Reduction in GHG emissions, potential to save (199.7 thousand Mt. CO_2 eq., improved public health and land use opportunities through waste reduction. CH_4 reduction 7.9 thousand tons.	[16]
Makkah	Plastic Waste	168.4 thousand ton yearly (2016).	-Generated by locals and pilgrims. -High during Ramadan and Hajj. -Mixed with food and packaging waste. -Clogging and slow degradation.	-Approx. 80% yield efficiency. -Liquid and gas fuels: 320 ton/day. -489 GWh electricity. -134-thousand-ton liquid fuel.	GHG emissions reduction 25% lower than incineration. -CH_4 reduction 7.9 thousand ton. -GWP reduction 199.7 thousand Mt. CO_2 eq. -199.7 thousand Mt CO Converts plastic waste into liquid fuel.	[34]
Madina (Hajj/Umrah)	Plastic wase (20% of MSW)	177.39 thousand tons (from local and Hajj/Umrah visitors).	-	-141.91 million kg pyrolytic oil generation 5619.8 TJ generation 58.81 MW continuous electricity. -Efficiency: 33%	Alleviates waste management issues, generates jobs. -Diverts waste from landfills, produces fuel.	[141]
KSA	Waste Tires	-Shredded tires (kg scale per run, prototype).	-Batch pyrolysis reactor, 321 °C, oxygen-free.	-36 wt.% fuel oil, 43 wt.% carbon black. -Fuel density 0.783 g/cc. -Comparable to diesel and natural gasoline.	-Reduces open burning/landfill disposal. -Decreases environmental pollution.	[142]
KSA	Date Palm Biomass	-345 thousand tons/year total. -50% of total date palm waste processed = 172,500 tons.	Fast Pyrolysis, 500–525 °C, fluidized bed, 10 tons/day.	-Produces bio-oil (38.8%), char (37.2%), Syngas (24%) of feedstock. -Annual energy yield 12.12 GWh.	-Reduces GHG emissions (Approx. 2029 tons CO_2/year). -Valorizes waste.	[15]
KSA	Plastic waste	-	Pyrolysis	-Energy recovery via syngas/bio-oil.	-Required emission control.	[10]
KSA	Scrap Tires	1835 ton/day	Vacuum Pyrolysis, 350–450 °C, oxygen-free.	-Significant oil yield. 45–55% oil yield. -Calorific value: 32–37 MJ/kg. -(30–35%) carbon black. -(10–15%) gas.	-Reduces landfill use, prevents contaminants, CO_2 emission reduction.	[143]

In urban settings, where waste composition changes seasonally, Rehan et al. [16] investigated the pyrolysis of mixed plastic waste in Makkah. Operating temperatures between 300 °C and 500 °C allowed the process to yield up to 80% liquid fuel with high energy content, indicating significant potential for electricity generation. This study went beyond national estimates by incorporating projections for future waste generation. However, it made assumptions about consistent feedstock quality and uninterrupted plant operation—conditions that may not accurately represent the variability present in urban MSW.

Expanding on this, Nizami [34] framed pyrolysis within the concept of a waste-based biorefinery, assessing aspects beyond energy recovery, including fuel quality, GHG reduction, and the potential for fossil fuel substitution. The resulting pyrolysis oil, characterized by low sulfur content and a high cetane number, supports applications in both power generation and transportation. Despite these advantages, the analysis, like many others, relied significantly on theoretical modeling instead of operational data. Rehan et al. [141] introduced a more integrated approach in Madinah, combining AD for organic waste with pyrolysis for plastics. This highlighted pyrolysis as a targeted solution for high-carbon, non-biodegradable fractions, while also addressing the economic and operational challenges often overlooked in energy-centric studies.

Experimental research has further validated the feasibility of pyrolysis for specific waste types. Dawoud [142] demonstrated the effectiveness of batch pyrolysis for scrap tires, successfully producing fuel oil and carbon black with measurable yields and acceptable quality. However, the constraints of batch-scale operations limit the direct application of these findings to industrial-scale scenarios. Yahya et al. [143] tackled these limitations by examining vacuum pyrolysis of scrap tires within a techno-economic and environmental framework, revealing that reactor design and process optimization significantly enhance fuel yield, economic performance, and payback periods. The adaptability of pyrolysis is also showcased in the processing of biomass residues. Yahya [15] investigated fast pyrolysis of date palm waste, an abundant agricultural by-product, confirming its capability to produce bio-oil, biochar, and syngas with favorable energy and economic outcomes.

Collectively, these studies illustrate a strong consensus on the technical potential of pyrolysis as a flexible WtE technology capable of processing diverse waste streams in Saudi Arabia, consistently delivering energy and economic benefits. However, most research relies on modeled scenarios or small-scale experiments, revealing a critical gap in large-scale, long-term operational data under the heterogeneous and seasonally variable conditions typical of urban areas in the country. Addressing this gap is essential for transitioning pyrolysis from a promising theoretical solution into a reliable and sustainable component of municipal waste management strategies aligned with Saudi Arabia's Vision 2030.

4.1.5. Pre-Treatment Step for Thermochemical Conversion Technologies

Pre-treatment is a crucial phase in thermochemical WtE conversion technologies, significantly impacting feedstock quality, energy efficiency, and the stable operation of processes like combustion and pyrolysis [33]. MSW designated for thermochemical conversion typically undergoes several preparatory processes, including mechanical size reduction, material separation, crushing, and drying, prior to energy recovery [29,33]. These processes are vital for heterogeneous waste streams that include plastics, paper, and other combustible materials, as they enhance feedstock uniformity and mitigate operational variability [29]. Pre-treatment effectively lowers moisture content, eliminates non-combustible and inert fractions, and boosts the calorific value of the waste, thereby improving conversion efficiency and minimizing technical challenges during thermal processing. In systems utilizing RDF, pre-treatment is essential for transforming mixed MSW into a standardized, high-

calorific fuel that is appropriate for use in power generation facilities and co-combustion applications [29,33].

RDF

RDF is a high-calorific, combustible fraction derived from MSW and is increasingly acknowledged as a viable alternative to coal in power generation plants [29]. The production process of RDF encompasses several stages, including size reduction, material separation, crushing, drying, and palletization, leading to the formation of fuel types such as pellets or chalk-like solids. These transformations enhance the handling and combustion properties of the fuel [29,66]. The suitable waste streams for RDF production primarily include paper, cardboard, plastics, wood, textiles, leather, and other mixed combustible materials [5,66]. RDF technology has advanced significantly in Europe, where production surged from 1.4 million tons per year to 12.4 million tons per year between 2000 and 2005. It is widely utilized in industrial co-incineration, particularly in the pulp, paper, and wood sectors [29]. Experiences from countries like India and the United States further demonstrate the feasibility of RDF, with facilities operating at capacities between 150 and 2000 tons per day [29,66].

RDF boasts a high calorific value of approximately 0.145 kW/kg and achieves an overall electricity generation efficiency of about 18% [5,29]. It plays a crucial role in diverting waste from landfills, replacing fossil fuels, and improving waste management practices, although effective air pollution control and proper ash handling are essential due to emissions generated during combustion [5,66]. Despite its advantages, RDF faces economic and operational challenges, such as significant capital investments, land acquisition, the necessity for extensive pre-treatment infrastructure, and labor-intensive operations, all of which can result in higher unit costs in comparison to other WtE technologies [5,29]. Nonetheless, RDF remains a critical option in thermochemical WtE, especially in urban and industrial environments, with considerable potential for electricity generation; for instance, it is estimated that Saudi Arabia could generate around 1.55 TWh annually if all suitable waste streams are fully utilized [5,66]. The associated benefits and challenges of RDF are extensively discussed in Table 11.

Table 11. Benefits and drawbacks of RDF technology.

Category	Aspect	Description	Ref.
Benefits	Waste Treatment Capacity	RDF is effective for large-scale MSW streams and industrial combustible waste fractions, capable of treating a significant portion of MSW in urban areas.	[33,34]
	Waste Volume Reduction	It facilitates substantial landfill diversion by converting combustible waste into fuel pellets.	[29,33]
	Energy Recovery Potential	RDF serves as an alternative fuel for coal-fired power and industrial plants, achieving an overall electrical efficiency of approximately 18%.	[34,65]
	Environmental Performance	The addition of $Ca(OH)_2$ during RDF combustion reduces dependency on fossil fuels and lowers emissions of SO_2 and polycyclic aromatic hydrocarbons.	[65,144–146]
	Circular Economy Compatibility	RDF transforms waste into eco-friendly alternative fuel pellets that can be reused in industrial applications.	[33,65]
	Urban Applicability	The technology is well-suited for large urban and industrial areas, especially where pulp, paper, wood, and sawmill industries are prevalent.	[29,65]

Table 11. *Cont.*

Category	Aspect	Description	Ref.
Drawbacks	Air Pollutant Control Requirements	Emissions resulting from RDF combustion necessitate advanced flue gas treatment and emission control systems.	[29]
	Residual Waste Generation	The process generates ash and mineral residues that require appropriate handling and disposal.	[29,34]
	High Capital Investment	There are significant costs associated with land acquisition, multistage preprocessing, pelletization, and specialized equipment.	[29]
	Operational Complexity	The multistage processing, which includes drying, chemical addition ($CaO/Ca(OH)_2$), and pellet formation, adds to the complexity of the system.	[29,65]
	Sensitivity to Feedstock Variability	Maintaining consistent waste segregation and quality control is essential to ensure optimal pellet performance.	[33]
	Skilled Labor Requirement	The operation and maintenance of RDF facilities entail high labor costs due to the need for skilled labor.	[33]

RDF presents a clean and efficient method for producing an eco-friendly alternative fuel for coal-powered industries. The RDF particles are thoroughly mixed with binders such as calcium hydroxide, and CaO is added during production [144,145]. In the presence of water, CaO reacts to form $Ca(OH)_2$. When flue gas is used as the drying gas, this compound reacts with CO_2, yielding $CaCO_3$ [146]. The RDF is ultimately shaped into pellets with dimensions of approximately 15 mm in diameter and 50 mm in length, containing around 11% or more particulate calcium hydroxide [65]. This mixture, upon combustion, results in an effluent gas featuring reduced levels of SO_2 and polycyclic aromatic hydrocarbons compared to similar materials lacking calcium hydroxide [147]. RDF is predominantly utilized in the pulp and paper industry, as well as in the wood industry, making facilities relatively small and specifically tailored for industrial applications [65].

Recent studies in Saudi Arabia illustrate a growing interest in RDF as a crucial WtE option for sustainable MSW management. At the national level, Nizami et al. [33] evaluated the potential of RDF produced from high-calorific combustible fractions of MSW, including paper, cardboard, plastics, textiles, wood, and mixed waste. Their investigation utilized mechanical pre-treatment processes such as size reduction, separation, drying, and pelletization. The study identified RDF as a viable alternative to coal for power generation, achieving an overall electrical efficiency of approximately 18%. Based on Saudi Arabia's MSW generation rates, the researchers estimated that around 4.0 Mt/year of waste, accounting for 26.3% of total MSW, is suitable for RDF production, which could correspond to an electricity generation potential of about 1.55 TWh/year [33]. However, they also noted that the deployment of RDF faces challenges such as high capital investment, land requirements, extensive pre-processing infrastructure, and the necessity for skilled manpower [33].

Building upon this national assessment, Nizami et al. [34] explored the feasibility of integrating RDF within a waste-based biorefinery framework in Makkah city. The city experiences exceptionally high MSW generation due to seasonal population surges during Ramadan and Hajj. The study reported baseline MSW generation of approximately 2.4 kt/day, with increases to 3.1 kt/day during Ramadan and 4.6 kt/day during Hajj. Within the proposed biorefinery system, RDF derived from combustible MSW fractions was utilized alongside other WtE technologies to treat a portion of the waste stream. The results indicated that RDF production could reach 150,000 t/year, generating about 200 GWh/year of electricity and yielding a net annual revenue of 117.3 million SAR. The authors concluded

that integrating RDF with complementary WtE technologies can significantly reduce landfill dependency, mitigate GHG emissions, and support renewable electricity generation in densely populated urban centers like Makkah [34].

Complementing these findings, Ouda et al. [65] assessed WtE scenarios for major cities in the Western Province of Saudi Arabia, including Jeddah, Makkah, and Madina, focusing on an RDF with biomethanation configuration. In this approach, MSW is segregated into organic and inorganic fractions, with organic waste treated through biomethanation and the high-calorific inorganic fraction converted into RDF for energy recovery. Based on projected MSW generation until 2032, the study estimated electricity generation capacities of approximately 87.3 MW in Jeddah, 42.4 MW in Makkah, and 29.9 MW in Madina under this scenario. Although the Mass Burn option demonstrated a higher theoretical power output, Ouda et al. [65] concluded that the RDF with biomethanation scenario offers a more balanced and environmentally favorable solution by promoting waste segregation, renewable energy generation, and substantial landfill diversion. An overview of the implementation of RDF for MSW management in Saudi Arabia is presented in Table 12.

Table 12. Overview of RDF technology for MSW in KSA.

City	Waste Type	Operating Conditions	Energy Recovery and Performance	Environmental Impact	Ref.
Makkah	Suitable MSW fraction (paper, cardboard, plastics, wood, textiles)	Segregation, drying, pelletization, combustion	Approx. 200 GWh/year electricity; 18–30% efficiency.	Landfill diversion; reduction in GHG and fossil fuel use.	[34]
KSA	Suitable MSW fraction (paper, cardboard, plastics, wood, textiles, leather, other)	Pre-processing (sorting, shredding, drying, pelletization); combustion for power generation.	Electricity potential approx. 1.55 TWh/year from approx. 4 Mt/year RDF feedstock.	Reduced landfilling; requires air pollution control and residue management.	[33]
Jeddah	Inorganic MSW Fraction	Waste segregation; RDF production from inorganic waste; biomethanation for organic fraction.	Estimated electricity generation: 87.3 MW by 2032	Reduces reliance on landfills and mitigates CH_4 emissions.	[65]
Makkah	Inorganic MSW Fraction	Waste segregation; RDF production from inorganic waste; biomethanation for organic fraction.	Estimated electricity generation: 42.4 MW by 2032	Reduces reliance on landfills and mitigates CH_4 emissions.	[65]
Madinah	Inorganic MSW Fraction	Waste segregation; RDF production from inorganic waste; biomethanation for organic fraction.	Estimated electricity generation: 29.9 MW by 2032	Reduces reliance on landfills and mitigates CH_4 emissions.	[65]

4.2. Biochemical WtE Conversion Technologies

Biochemical WtE conversion technologies utilize biological processes to decompose the biodegradable fraction of MSW and recover energy in the form of biogas [55,148]. Compared to thermochemical technologies, these pathways operate under lower temperature and pressure conditions, resulting in lower air emissions and improved environmental performance [55,148]. They are particularly suitable for waste streams with high moisture and organic content, which characterize MSW in many regions, including Saudi Arabia [55,148].

Among biochemical options, AD has received considerable attention due to its ability to simultaneously reduce waste volumes, generate renewable energy, and recover nutrients in the form of digestate [33]. This process relies on controlled microbial activity to convert organic waste into biogas suitable for heating and electricity generation, thereby contributing to energy diversification and sustainability objectives [55]. However, despite its environmental and economic advantages, the applicability of AD is strongly influenced by operational scale, feedstock quality, and urban context.

Anaerobic Digestion

AD is a well-established biochemical WtE conversion technology widely applied to treat biodegradable waste streams such as the organic fraction of municipal solid waste (OFMSW), food waste, agricultural residues, animal manure, and slaughterhouse waste [19,63,149]. This process involves the biological and chemical degradation of organic waste into biogas and digestate [150,151]. Biogas typically contains 60–80% CH_4 and can be used for electricity generation, heating, or upgraded to biomethane [136,139,152,153]. Biogas, mainly composed of CH_4 and CO_2, can be directly used for heat and electricity generation or upgraded to biomethane for injection into gas grids or transport applications [19,136,150]. The digestate, enriched with carbon and nitrogen compounds, can be reused as an organic fertilizer, thereby closing nutrient loops and supporting circular economy principles [4,55]. The conversion process occurs through a sequence of interdependent biochemical stages, includes hydrolysis, acidogenesis, acetogenesis, methanogenesis, and sulfur reduction, each mediated by specific microbial communities, as illustrated in Figure 5 [19,136,150]. The strong interdependence between these stages explains the sensitivity of AD to operational disturbances and feedstock variability [150,151]. Stable reactor performance therefore requires strict control of operating parameters, including temperature (typically 35–70 °C), pH, moisture content, and hydraulic retention time [19,63].

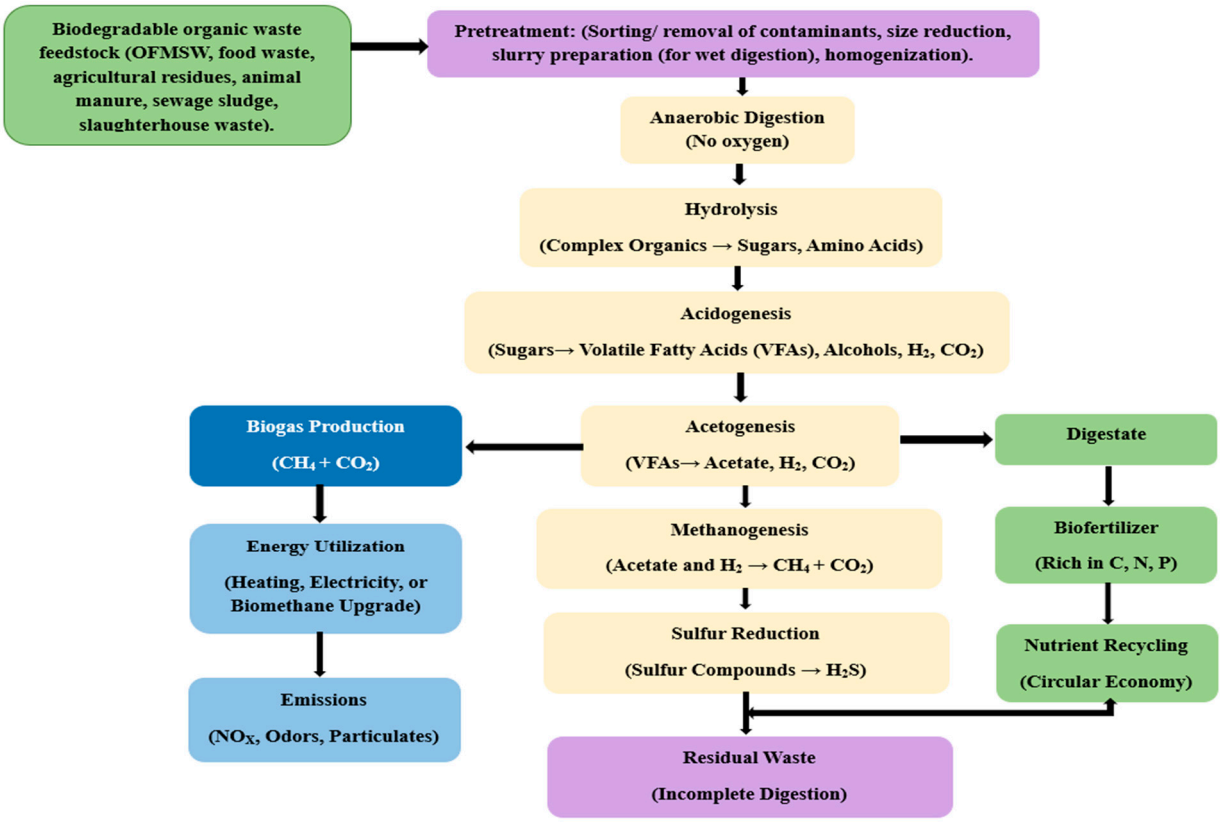


Figure 5. Flowchart of the AD process for organic WtE conversion.

AD offers several advantages that justify its widespread consideration for organic waste management. As summarized in Table 13, AD achieves substantial landfill diversion while simultaneously recovering renewable energy, with reported biogas methane concentrations ranging between 60% and 80% [136,152,153]. Compared to thermochemical technologies, AD generally results in lower air emissions, reduced odor generation, and lower overall GHG impacts [136,154,155]. The environmental benefits extend beyond energy recovery, as diverting organic waste from landfills significantly reduces leachate formation and uncontrolled methane emissions, which are major contributors to soil, groundwater contamination, and climate change [19,154].

Table 13. Benefits and drawbacks of AD technology.

Category	Aspect	Description	Ref.
Benefits	Waste Treatment Capacity	AC can process a diverse array of organic wastes, including OFMSW, food waste, sewage sludge, agricultural residues, animal manure, and slaughterhouse waste, as long as high organic content is ensured.	[19,63,149]
	Waste Volume Reduction	Diverting organic waste from landfills significantly decreases landfill volume and minimizes leachate generation.	[87,136]
	Energy Recovery Potential	The process generates biogas with a CH_4 content of 60–80%, which can be used for heating, electricity, or upgraded to biomethane.	[136,153,156]
	Environmental Performance	AD produces lower air emissions compared to incineration, gasification, and pyrolysis, and the controlled process helps minimize pollution.	[87,136,154]
	Circular Economy Compatibility	The digestate can be repurposed as biofertilizer, facilitating nutrient recycling (nitrogen and phosphorus) back into the soil.	[136,152,157]
	Urban Applicability	AD can be implemented at various scales; however, its application in densely populated urban areas encounters logistical and operational challenges.	[158]
Drawbacks	Air Pollutant Control Requirements	The combustion of biogas may emit NO_x, odors, and particulates, necessitating emission control measures.	[136,154]
	Residual Waste Generation	AD does not fully digest all waste components, residual digestate and unusable by-products may remain after the process.	[136]
	High Capital Investment	Compared to compositing, the initial capital and operational costs are medium to high, requiring infrastructure-intensive systems.	[19]
	Operational Complexity	The multi-stage biochemical process demands stringent control over temperature, pH, moisture, and retention time for optimal performance.	[19,63,159]
	Sensitivity to Feedstock Variability	The efficiency of the process is highly dependent on the quality of the feedstock. Contamination with heavy metals can diminish efficiency and product value.	[136]
	Skilled Labor Requirement	The operation requires trained personnel of process control, monitoring, and maintenance of the reactors.	[158,159]

Various types of anaerobic digesters exist, determined by factors such as feedstock properties (wet or dry waste), feedstock loading systems (continuous or batch processes), operating temperature conditions (thermophilic or mesophilic), selected technology (single-stage, two-stage/phase, or multistage processes), and feedstock retention time [4]. The strengths and limitations of AD, including its waste treatment capacity, energy recovery

potential, environmental performance, and operational challenges, are encapsulated in Table 13.

However, despite these advantages, AD faces several limitations. The process is sensitive to feedstock variability, operational complexity, and requires skilled labor and efficient emission control systems [63]. It is also inherently slow and affected by variations in feedstock composition and contamination levels, which can impact process stability and CH_4 yield [63,136]. Additionally, AD does not fully degrade all waste components, potentially leading to residual waste streams or digestate containing contaminants that limit market value [136]. The implementation of AD encounters additional constraints related to space availability, feedstock logistics, and odor management. These factors partially explain its lower adoption rate compared to incineration-based WtE systems in densely populated areas [158]. Furthermore, while AD generally incurs lower capital and operational costs than thermal technologies, the initial investment for reactors, preprocessing units, and gas handling systems remains substantial, potentially hindering large-scale deployment [87,136].

Saudi Arabian case studies presented in Table 14 further confirm the technical feasibility and energy recovery potential of AD under local conditions. National-scale assessments indicate that optimized AD of food waste could generate up to 2.99 TWh/year of electricity [33], while city-scale applications in Makkah and Madinah demonstrate electricity outputs of 164.5 GWh/year and 15.64 MW of continuous power, respectively [34,141]. These results are strongly linked to the high and relatively consistent organic content of Saudi MSW, where food waste represents more than 50% of total waste in major cities [33,34] and around 40% in Madinah [141]. Such feedstock consistency provides a structural advantage for AD by enabling predictable biogas yields and stable reactor operation. Energy recovery through AD is consistently reported as reliable under conventional mesophilic conditions, with electricity conversion efficiencies around 35% [34,141]. The effectiveness of AD is tied to the quantity and quality of segregated organic waste, making large-scale adoption sensitive to social and operational variables such as household participation, collection systems, and seasonal fluctuations (e.g., Hajj and Ramadan peaks).

Table 14. Overview of AD technology for MSW in KSA.

City	Waste Type	Waste Generation, t/day	Operating Conditions	Energy Recovery and Performance	Environmental Impact	Ref.
KSA (Riyadh, Jeddah, Dammam, Makkah)	Organic waste (Food waste 50.6%)	Estimated 5000 t/day (Ramadan, first 3 days)	-	Electricity generation included in national estimate (part of 2.99 TWh/year). AD process efficiency: 25%	Reduces GHG emissions, provides nutrient-rich digestate for agricultural use, and conserves landfill space. Co-products: Digestate (Fertilizer).	[33]
Makkah	Organic waste (Food waste)	2400–4600 (depending on season)	Biochemical AD, mesophilic/thermophilic, batch/continuous.	-Biogas production: 76.9 million m^3/year. Electricity potential: 164.5 GWh/year.	-CH_4 reduction: 20.2 thousand tons. -GWh reduction: 505 thousand Mt. CO_2 eq. -Reduction in organic pollutants by 50%.	[34]
Madina (Hajj/Umrah)	Food waste (40% of MSW)	354.79 thousand tons (from local and Hajj/Umrah visitors).	Biochemical AD	-Biogas production: 64.07 million m^3 generation 1409.63 TJ. -Electricity potential:15.64 MW continuous. -AD Efficiency: 35%	-Landfill diversion: Cost saving US $63.51 million/year.	[141]

Table 14. *Cont.*

City	Waste Type	Waste Generation, t/day	Operating Conditions	Energy Recovery and Performance	Environmental Impact	Ref.
KSA	Food waste	60,547 t/day	Collected and processed via AD	-Electricity: 2.33 TWh/year	-Lower GHG emissions than landfill/incineration.	[10]
KSA	Agricultural crop residues	4767 t/day	Collected residues, processed via AD	-Electricity: 1.75 TWh/year	-Lower GHG emissions (0.3 Mt. CO_2 eq/year)	[10]
KSA	Animal wastes	18,569 t/day	Collected and processed via AD	-Electricity: 375.48 GWh/year	-GHG emissions: 63.08 kt CO_2 eq/year.	[10]
KSA	Sewage wastes	2368 t/day	Dry sludge from wastewater treatment, processed via AD	-Electricity: 0.67 TWh/year	-GHG emissions: 0.11 Mt CO_2 eq/year.	[10]
Riyadh	Organic MSW (36%)	3500 t/year (About 9.6 t/day)	-Source-separated, fed to AD plant. Remaining waste: part MRF, incineration, landfill.	Biogas production, electricity to grid.	-Reduced GWP, AP, EP vs. landfill.	[148]
Riyadh	Organic MSW	3500 t/year (About 9.6 t/day)	Source-separated, fed to AD plant. 100% of organic waste. 100% recyclables to MPF. Minimal landfill/incineration.	Maximum biogas production, electricity to grid.	-Lowest GWP, AP, EP. -Highest environmental benefits.	[148]
Tabuk	Organic Waste	550,716,088 kg (2023). Projected 575,846,338 kg (2050).	Organic waste diverted from landfills to AD.	-In 2024: 99,741 m^3 convert to 1,052,267 kWh (1 million kWh). -In 2025: 1,514,931 m^3 biogas convert to 15,982,521 kWh. (15 million kWh).	-Reduces CH_4 emissions from landfill. -Decrease GHG. -Mitigates soil and groundwater contamination.	[160]
Jeddah/Jabal Shamah	OFMSW (up to 72%)	-	-AD with natural zeolite (mordenite) additive 5–10% wt, mesophilic.	-CH_4 production increased up to 3. -NH_4^+ removal. -Digestate for fertilizer.	-Enhanced CH_4 yield reduces fossil fuel reliance. -Lower ammonia toxicity in digestate.	[126]

Economic analyses consistently portray AD as competitive relative to other WtE technologies. Nizami et al. [34] estimated low capital costs ($0.1–0.14 per ton) with minimal labor requirements, and Rehan et al. [141] and Abdel Daiem and Said, [10] affirm that net economic benefits can be realized via electricity generation, landfill diversion, and carbon credits. However, this economic optimism must be tempered, the feasibility of AD in practice is contingent on effective pre-treatment, reliable feedstock supply, and supportive policies. Without systemic coordination, cost savings may be overestimated, particularly in urban centers where space constraints and high organic contamination rates may compromise process stability. Life cycle and environmental assessments also consistently show that AD outperforms landfilling and some thermochemical options [34,148,160]. Almansour and Akrami, [148] shows substantial reductions in global warming potential, acidification, eutrophication, and ozone depletion for Riyadh scenarios involving AD, while Nizami et al. [34] confirms maximal reductions in CH_4 emissions and GWP in Makkah compared to pyrolysis and RDF. Lakhouit [160] further quantifies the long-term environmental burden of landfilling in Tabuk, highlighting the mitigation potential achieved through AD-mediated biogas recovery.

Despite these advantages, the AD faces significant technical, spatial, and operational challenges that limit its scalability, particularly in dense urban environments. One of the primary constraints is the strong dependence of AD performance on feedstock quality. Variations in organic content, contamination with heavy metals or plastics, and seasonal fluctuations can disrupt microbial activity, reduce methane yields, and compromise diges-

tate quality [63,136]. These issues are particularly relevant in urban settings where effective source separation is difficult to enforce.

The multi-stage biochemical nature of AD requires continuous monitoring and precise control of temperature, pH, moisture, and retention time [19,63,159]. This complexity translates into a need for skilled labor, advanced monitoring systems, and robust process control, which can increase operational costs and reduce reliability when such expertise is limited [158,159]. Furthermore, AD is inherently slower than thermochemical technologies, making it less responsive during peak waste generation periods such as Hajj and Ramadan, when waste quantities increase sharply [34,141].

Spatial constraints also play a critical role in limiting urban deployment. AD facilities require substantial land for reactors, preprocessing units, digestate storage, and odor control systems [158]. These spatial and logistical requirements partially explain the lower adoption of AD compared to incineration-based WtE systems in densely populated cities [158]. Odor management and community acceptance further complicate siting decisions, especially in residential or mixed-use urban areas [158]. While AD is often described as a low-cost technology, Table 13 and the Saudi case studies in Table 14 indicate that initial capital investment remains significant. Costs associated with reactor construction, feedstock preprocessing, gas handling, and emission control infrastructure can hinder large-scale deployment if not supported by coordinated waste collection systems and enabling policies [87,136]. As a result, the economic feasibility of AD may be overestimated when logistical and spatial constraints are not fully accounted for, particularly in metropolitan contexts.

Recent advances in process optimization provide promising pathways to address some of these limitations. For example, the addition of locally available natural zeolites, such as mordenite, has been shown to enhance CH_4 production by adsorbing inhibitory ammonium ions and stabilizing microbial activity, thereby improving reactor resilience under variable operating conditions [126]. Such locally tailored optimization strategies highlight the importance of adapting AD systems to regional waste characteristics rather than relying on generic reactor designs.

Overall, the Saudi case studies establish AD as a technically feasible, economically attractive, and environmentally beneficial approach to managing organic MSW. However, the success of AD hinges not solely on the reactor technology but on integrated waste management systems, effective source separation, continuous monitoring, and site-specific optimization.

4.3. Chemical WtE Conversion Technologies

Chemical WtE conversion refers to a set of technologies that employ chemical and physicochemical processes to turn waste materials into energy carriers or fuels. Unlike thermal WtE methods, which primarily derive energy through heat, chemical WtE is aimed at capturing the chemical energy inherent in organic and industrial waste, subsequently transforming it into liquid or gaseous fuels that can be utilized for energy production [29]. Unlike thermochemical technologies that rely on heat, chemical WtE pathways focus on fuel synthesis, making them particularly suitable for waste streams such as fats, oils, and lipid-rich residues that are unsuitable for direct combustion, thus playing a vital role in waste management and the generation of renewable energy [161,162]. Within this category, transesterification has emerged as a practical solution for valorizing lipid-rich waste fractions of MSW, particularly in urban environments with significant food and restaurant waste generation [33,34].

Transesterification

Transesterification is a chemical conversion process that transforms waste oils and fats into biodiesel and glycerol through reactions with alcohols in the presence of catalysts [33,161,162]. During this conversion, organic waste is transformed chemically into liquid biofuels, which can be used for energy generation either in their pure form or blended with conventional diesel [161,162]. Biodiesel produced via this route is sulfur-free, biodegradable, and can be used directly or blended with conventional diesel, reducing dependence on fossil fuels and lowering GHG emissions [163,164], as shown in Figure 6.

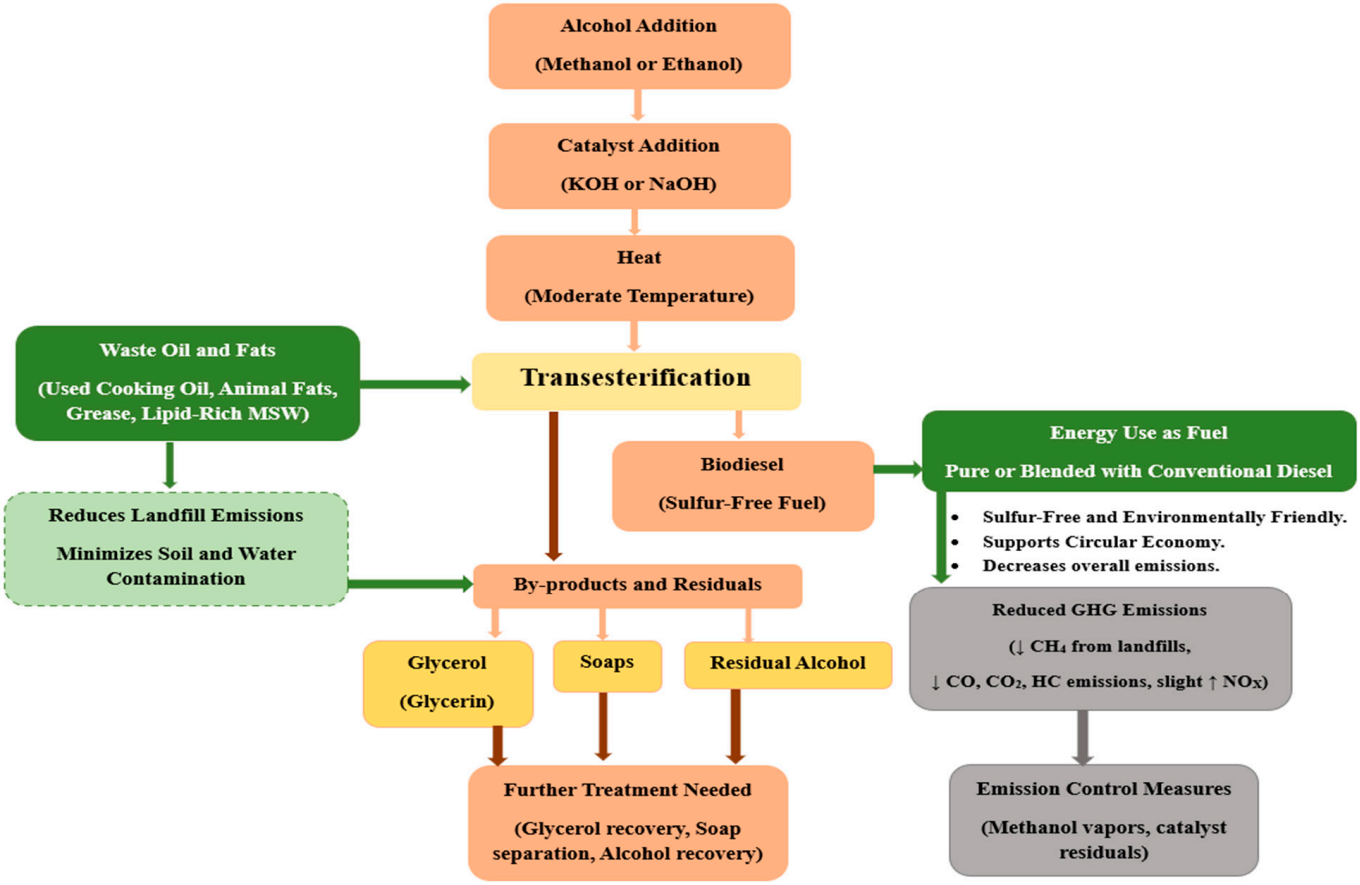


Figure 6. Flowchart of the transesterification process for converting waste oils and fats into biodiesel.

The benefits and challenges associated with transesterification, such as energy recovery, waste reduction, environmental advantages, and operational limitations, are discussed in detail in Table 15.

Table 15. Benefits and drawbacks of transesterification technology.

Category	Aspect	Description	Ref.
Benefits	Waste Treatment Capacity	Effectively manages the fats and oils fraction of MSW sourced from households and restaurants.	[33,165]
	Waste Volume Reduction	Decreases the quantity of organic fats and oils sent to landfills by diverting lipids from waste streams.	[33,34,165]
	Energy Recovery Potential	Generates high-energy biodiesel and glycerol as valuable by-products.	[33,165]

Table 15. *Cont.*

Category	Aspect	Description	Ref.
Benefits	Environmental Performance	Reduces CH_4 emissions from landfills while minimizing soil and water contamination, with decreased CO, CO_2, and hydrocarbon (HC) emissions, although a slight increase in NOx may occur.	[33,163,165]
	Circular Economy Compatibility	Transforms waste oils and fats into fuel, bolstering urban circular economy initiatives by converting these materials into biodiesel and glycerol.	[33,34,165]
	Urban Applicability	Well-suited for large cities with established collection networks for used oils and fats, making industrial-scale operations feasible in urban areas such as Makkah.	[33,34,165]
Drawbacks	Air Pollutant Control Requirements	Necessitates the management of alcohol vapors, achieving lower emissions compared to thermal WtE technologies; however, controls for methanol, potassium hydroxide, and residuals are still needed.	[33,34,165]
	Residual Waste Generation	Produces glycerol, soaps, and residual alcohol that require additional treatment.	[33,165]
	High Capital Investment	Initial costs for reactor and downstream processing equipment can be significant.	[33,165]
	Operational Complexity	Requires precise control over temperature, reaction time, and the alcohol-to-oil ratio.	[33,165]
	Sensitivity to Feedstock Variability	Performance is influenced by feedstock purity; the presence of water and impurities can diminish conversion efficiency, and the system is reliant on fat content, limiting its capability to process non-lipid MSW.	[33,34,165]
	Skilled Labor Requirement	The operation demands trained personnel for effective handling and processing	[33,163,165]

Recent Studies have highlighted the tangible potential of transesterification as a chemical WtE technology in Saudi Arabia. Nizami et al. [33] observed that MSW in the Kingdom contains a substantial proportion of fats and oils, notably from food and restaurant waste, which can be effectively valorized through transesterification. This process not only recovers energy from the lipid waste fraction but also aids in reducing CH_4 emissions, diverting waste from landfills, and reinforcing circular economy initiatives [33]. In Makkah, transesterification converted approximately 64,000 t/year of lipid-rich food and slaughter waste into 62.5 kt/year of biodiesel and 6.38 kt/year of glycerol, achieving an impressive 98% conversion efficiency and generating 244.2 GWh of electricity, leading to a net economic gain of 76.5 million SAR per year [34].

Further research conducted in Jeddah has underscored the effectiveness of natural zeolites as catalysts in enhancing transesterification performance, demonstrating that their thermal stability, porosity, and surface area significantly boost biodiesel production from used oils and animal fats [126]. Additionally, Yaqoob and Ali [163] illustrated the application of biodiesel sourced from waste chicken fat in high-pressure diesel engines. Their findings indicated that a 10% biodiesel blend (DB10) increased torque and brake power while simultaneously reducing emissions of CO, CO_2, and hydrocarbons (HC), thereby affirming the practicality of transesterification as a viable Chemical WtE strategy that yields renewable fuel, supports circular economy practices, and does not necessitate modifications to existing engines. An overview of the implementation of transesterification for MSW management in Saudi Arabia is presented in Table 16.

Table 16. Overview of transesterification technology for MSW in KSA.

City	Waste Type	Waste Generation, ton/day	Operating Conditions	Energy Recovery and Performance	Environmental Impact	Ref.
KSA (Riyadh, Jeddah, Dammam)	MSW (Food waste, used cooking oil, fats)	Food waste: approximately 7.7 million ton/year total (approximately 0.71 kg/capita/day) Oil/fats: included in food waste fraction	Collected from households, restaurants, and food processing units. No pre-treatment other than filtration/drying.	Conversion oils/fats to biodiesel. High calorific energy output. Reduces landfill CH_4.	-Reduces untreated oil disposal. -Lower CH_4 emissions. -Contributes to renewable energy and circular economy.	[33]
Makkah	MSW (Food fats)	64,000 ton/year (fat fraction)	Collected and separated for chemical WtE processing	Biodiesel 62.5 kt/year. Glycerol 6.38 kt/year. 244.2 GWh electricity.	Reduces CH_4 by 3026 tons. GWh reduction 75.7 kt CO_2 eq.	[34]
Jeddah	Animal fats/used oil from MSW	-	Collected and pretreated. Transesterification with zeolite catalyst.	Biodiesel (fatty acid methyl easter (FAME)) production free fatty acids (FFA) conversion (46% with unmodified natural zeolite); mesopore modification improves efficiency.	Diverts lipid-rich MSW from landfill, reduces potential CH_4 emissions; partial renewable energy generation.	[126]
KSA	Waste Chicken Fat	-	Experimental study in high-pressure diesel engines; blends of diesel and biodiesel (DB10, DB15, DB20)	DB10: 7.93% higher torque, 6.1% higher brake power; improved combustion efficiency.	DB10: CO decrease 16.66%, CO_2 decrease 10.79%, HC decrease 10.79%, and Nox increase 0.39%	[163]

Transesterification contributes to landfill diversion of lipid-rich waste, reduces methane emissions, and supports circular economy initiatives by converting waste into valuable fuels and by-products [34,166]. Experimental engine studies further confirm the practical usability of biodiesel blends without requiring engine modification, while achieving reductions in CO, CO_2, and HC emissions [163].

Despite its advantages, transesterification faces distinct logistical and operational limitations that restrict its broader application. The technology is highly dependent on the availability, purity, and consistent collection of lipid-rich waste streams [33,34,165]. Unlike AD, which can process mixed organic waste, transesterification is limited to fats and oils, making feedstock collection and segregation a critical necessary. Urban implementation requires well-established collection networks for used cooking oils from households, restaurants, and food processing facilities [165]. In the absence of organized collection systems, feedstock losses and contamination can significantly reduce conversion efficiency and economic viability. Additionally, the process is sensitive to water content and impurities, which can impair reaction efficiency and increase downstream treatment requirements [33,34,165].

Transesterification requires precise control of reaction parameters, including temperature, alcohol-to-oil ratio, and catalyst dosage, increasing system complexity and skilled labor demand [33,165]. Capital costs associated with reactors and downstream purification units remain relatively high, particularly when compared to biological treatment options [33,165]. Collectively, these studies demonstrate that transesterification serves as a crucial chemical WtE pathway for enhancing the lipid fraction of MSW in urban Saudi Arabia. It complements other WtE technologies conversion for recyclables, thereby facilitating a comprehensive waste-based biorefinery approach. This synergy reveals the dual benefits of transesterification.

4.4. Integrated WtE Conversion Technologies with Recycling and Waste Segregation

Several studies conducted in Saudi Arabia have examined integrated MSW management frameworks in which WtE technologies are combined with recycling [2,31,62,65]. These studies collectively demonstrate that integrated systems represent a strategic pathway to balance energy recovery, material recovery, and environmental protection in alignment with Saudi Vision 2030 objectives.

National-scale assessments have evaluated the integration of WtE with recycling under total incineration and incineration with recycling scenarios, showing that the separation of recyclable fractions prior to incineration reduces the overall electricity generation potential but enhances resource efficiency and environmental performance [2,65]. These studies further extended the role of WtE beyond electricity generation by linking MSW-derived energy to energy-intensive sectors such as reverse osmosis desalination, illustrating cross-sectoral synergies between waste management, energy production, and water security in Saudi Arabia [2].

City-scale investigations, particularly in Riyadh, Jeddah, Makkah, and Madinah, provide additional evidence supporting integrated WtE–recycling systems [31,65]. LCA–based analyses comparing landfill-dominated systems with scenarios incorporating recycling, anaerobic treatment of organic waste, and residual WtE consistently report significant reductions in GHG emissions and landfill dependency when integrated approaches are adopted [31]. While full mass-burn incineration scenarios achieve the highest electricity generation, scenarios that prioritize recycling and organic waste diversion demonstrate improved environmental performance and closer alignment with circular economy principles [31,65].

In addition to technological integration, socio-technical frameworks such as the 3R-WtE approach emphasize the role of behavioral and institutional factors in enhancing system performance [62]. Community-level waste reduction and recycling initiatives, when combined with centralized WtE facilities, have been shown to substantially reduce per capita waste generation while maintaining energy recovery from residual waste streams [62]. These findings highlight the importance of upstream waste reduction and recycling in improving the overall sustainability of WtE systems.

Across these studies, a common system configuration emerges, MSW is first subjected to source separation and centralized sorting; recyclable materials are diverted to material recovery facilities; organic fractions are treated through biological processes such as AD; and the remaining high-calorific, non-recyclable fraction is directed to thermochemical WtE technologies, including incineration, gasification, or RDF-based systems [2,31,65], as shown in Figure 7.

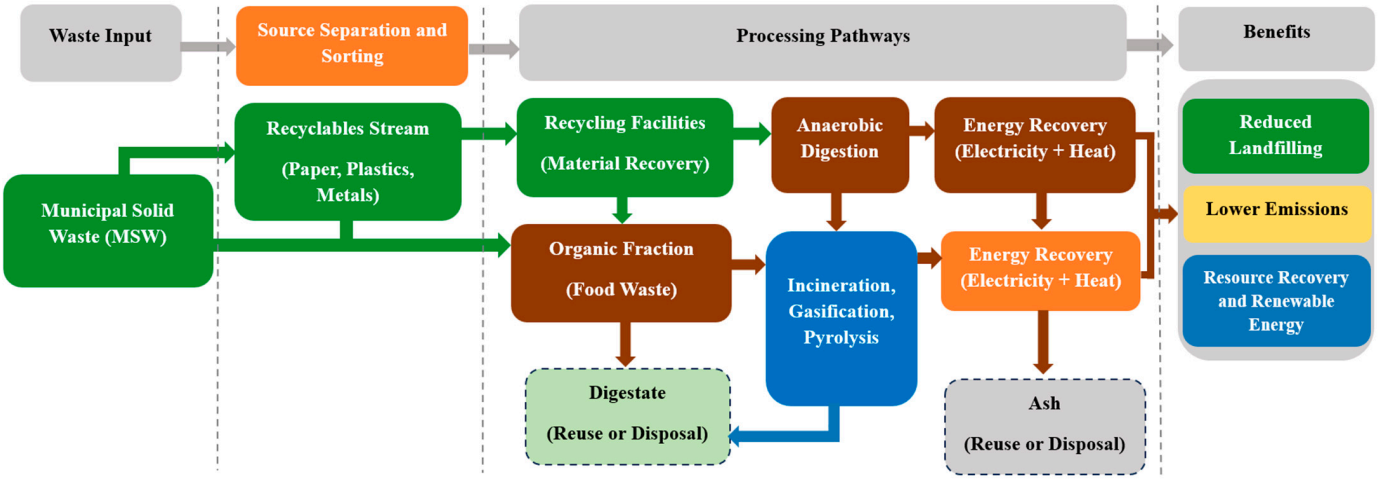


Figure 7. Integrated WtE and recycling system.

5. Economic Assessment of WtE Technologies in Saudi Arabia

A comprehensive evaluation of WtE technologies in Saudi Arabia highlights key distinctions in investment needs, operational expenses, and scalability, with various methods demonstrating distinct economic and operational characteristics across different systems, as summarized in Table 17.

Table 17. Economic assessment of WtE technologies in KSA.

Process	Initial Investment Cost (USD)	Capital Cost per ton (USD)	O&M Cost per ton (USD)	Total Cost per ton (USD)	Capacity (t/year)	Notes	Ref.
Plasma Gasification + pyrolysis	120,000,000	N/A	N/A	N/A	0.4 Mt/year	-Capital cost includes five plasma reactors (200 t/day each) covering manufacturing, transportation, utilities, labor, and fixed plant costs. -The total capital investment covers the manufacturing.	[48]
Plasma Gasification	120,000,000 (for 5 reactors)	N/A	N/A	N/A	200,000× 365 = 72,000 t/year	-5 reactors, 200 t/day each. -Average plastic input: 400,000 t/year. -2022 revenues: 5 million USD from diesel, 32–50 million USD from electricity.	[46]
Plasma Gasification	Approx. 38–40 million	Approx. 1060 USD/ton	N/A	151 USD/ton	100 t/day operation assumed at 330 days/year as stated in the study, thus the capacity is 33,000 t/year.	-Initial cost reported as 35 million EUR, waste treatment fee reported as 151 EUR/ton, O&M included within total cost. -Total electrical power requirement is 5000 kW, of which 2000 kW consumed internally by the plasma system, while 3000 kW sold is exported to the grid.	[82]
Gasification	1 million	55.6 USD	Total O&M cost/plant capacity = 14.48 USD/ton	Total cost = Total IC/capacity = 308,132/18,000 = 17.12 USD/ton	50 t/day × 360 day = 18,000 t/year	-50 t/day facility operating. -Total O&M cost = 260,632 USD/year. -Depreciation = 47,500 USD/year. -Total internal annual cost (IC) = Annual operating cost + Depreciation = 308,132 USD/year.	[25]

Table 17. *Cont.*

Process	Initial Investment Cost (USD)	Capital Cost per ton (USD)	O&M Cost per ton (USD)	Total Cost per ton (USD)	Capacity (t/year)	Notes	Ref.
Gasification of DPF	(Gasifier, electric heater, compressor, granulator, fabrication/installation): 10,300 SAR = 2747	0.57	0.17	0.74	5184 kg/year = 5.18 t/year	-Downdraft gasifier, optimized for (H_2 + CO + Rich syngas), air flowrate: 1 l/min, temperature: 900 °C, particle size: 6 mm. -Syngas production (H_2 + CO+ CH_4): 1493.2 kg/day. -Syngas cost: SAR 4.04/kg, potential for cost reduction with scaling.	[57]
Pyrolysis	N/A	17–25 USD/ton	2–3 USD/ton	N/A	-0.263 million ton (2016 MPW). -0.516 million ton (2040 projected MPW)	-Produces 0.21-million-ton liquid fuel, electricity 87.91 MW. -Produces 0.412-million-ton liquid fuel, electricity 172.8 MW.	[16]
Pyrolysis	17,000–25,000	17–25 USD/ton	2–3 USD/ton	19–28 USD/ton	-168,400 ton (2016 MPW)	-Produces 134-thousand-ton liquid fuel, electricity 489 GWh, net revenue 172.7 million SAR/year. -Thermochemical conversion of plastics to fuel oil, char, gas, high technology complexity.	[34]
AD	N/A	0.1–0.14 USD ton/year	N/A	0.2–0.28	430,000	-Lowest capital and operational costs. -Suitable for high-moisture food waste. -Low complexity and labor requirement. -Food waste only.	[34]
Transesterification	200,000–500,000	200–500	35–70	235–570	64 thousand ton (fats)	-High capital and O&M. -Produces biodiesel and glycerol. -Intermediate labor/complexity. -Biodiesel + glycerol. -98% conversion efficiency. -Intermediate complexity	[34]
RDF	7500–11,300	7.5–11.3	0.3–0.55	7.8–11.85	190 thousand ton.	-Converts mixed waste. -Intermediate complexity.	[34]
Fast Pyrolysis	2 million	11.57	172.92	297.22	3000	-10 tons/day unit. -Produces 0.388-ton bio-oil, 0.372-ton char, 0.24-ton syngas per ton feedstock. -Payback 2.57 years. -NPV positive. -IRR 36.45%.	[15]
Pyrolysis	226.94 million USD	N/A	-Lower than capital cost.	N/A	N/A	-Evaluated as a thermochemical option within integrated WtE.	[10]
Gasification (Crop residues)	355.22 million USD	N/A	-Lower than capital cost	N/A	N/A	-Highest cost among thermochemical methods.	[10]
AD (Food Waste)	59.36 million USD	2681 USD/ton	9595 USD/ton	12,276	22.11 Mt/year	-Eco-friendly, high-energy recovery, lower GHG emissions	[10]
AD (Agricultural Crop residues)	10.67 million USD	6136	21,953	28,089	1.74 Mt/year	-Moderate electricity, lower emissions than combustion.	[10]
AD (Sewage Waste)	9 million USD	10,416	37,229	47,645	0.864 Mt/year	-Low cost, eco-friendly, moderate electricity.	[10]
AD (Animal Waste)	7.12 million USD	1050	3756	4806	6.78 Mt/year	-Mostly cow and camel wastes, moderate electricity.	[10]
Incineration	High	N/A	-Higher than capital cost	N/A	National scale MSW (22.11 Mt/year)	-High electricity generation, high cost and strict emission control requirements.	[10]
Vacuum Pyrolysis	Total initial investment = 96,000 USD (220,810 USD/year)	64	136.65	147.21	1500	-Profitable operation with short payback period (0.71 years). -Net profit approximately 2.14 USD/tire. Initial investment of a 5 t/day pyrolysis plant. Annual fixed and variable operating costs.	[143]

As shown in Table 17, thermochemical WtE technologies typically require high initial capital investment but offer substantial potential for energy recovery. For example, plasma gasification is among the most capital-intensive methods, requiring investments up to 120 million USD for facilities integrating five plasma reactors that process 0.4 million tons per year. This investment includes all associated costs, such as manufacturing, transportation, utilities, and labor [48]. Larger plasma plants can generate revenues from both diesel and electricity, indicating high revenue potential if energy markets remain strong. For example, larger plasma plants operating at 200 tons per day have demonstrated revenue potential, generating approximately 5 million USD from diesel and between 32 and 50 million USD from electricity in 2022 [46]. Smaller plants, with capacities of 33,000 tons/year, necessitate initial investments of 38–40 million USD, and incur a waste treatment fee of about 151 USD/ton, which is integrated into operational costs [82]. However, these facilities are highly sensitive to electricity price fluctuations and energy market conditions, when electricity tariffs decline or fuel prices fall, revenue projections and payback periods deteriorate significantly. Detailed financial modeling of gasification and AD plants in Saudi Arabia has shown that key investment decision factors include facility generation capacity, electricity revenue, and capacity factor, indicating that energy price stability and robust revenue streams are critical for feasibility, especially for capital-intensive technologies like plasma gasification and conventional gasification [46,82,167].

Conventional gasification shows better economic flexibility at smaller scales due to lower initial costs. A facility processing 50 t/day may require around 1 million USD and achieve a total cost of 17.12 USD/ton when operational and depreciation costs are included [25]. Very small units, such as air gasification systems costing only ~2747 SAR (about 726 USD), producing syngas at a total cost of 0.74 USD/ton while operating at a capacity of only 5.18 t/year, demonstrate that micro-scale thermochemical systems can be economically competitive under certain local conditions [57]. Nonetheless, as scale increases, so do capital demands; crop residue gasification, for example, may require investments up to 355.22 million USD, underscoring that economies of scale and material costs heavily influence economic feasibility in large facilities [10].

Pyrolysis technologies exhibit a wide economic range that depends on feedstock type and plant scale. Municipal pyrolysis of plastics shows capital costs between 17–25 USD/ton and operational costs of 2–3 USD/ton [16], with projected electricity generation and liquid fuel production increasing with waste volume. In one scenario, a plant handling 168,400 t/year produced substantial energy output and net revenue, demonstrating that pyrolysis can be economically viable when feedstock supply is consistent and output markets (134,000 tons liquid fuels and 489 GWh electricity) are well priced [34]. Fast pyrolysis of date palm waste (10 t/day) reveals a payback period of 2.57 years and IRR of 36.45% with initial investment of 2 million USD [15], while tire vacuum pyrolysis (96,000 USD initial investment) shows a payback period of less than one year [143], highlighting that rapid returns are possible for certain feedstocks and products [15,143]. However, these results are sensitive to market prices for by-products, fuel values, and costs of scaling systems. Incineration, while capable of processing substantial amounts of MSW (22.11 million tons/year), typically involves high initial and operational costs, along with strict emission control requirements [10]. While this method is reliable for electricity generation, it generally lacks the economic attractiveness of plasma gasification and pyrolysis, particularly concerning energy recovery efficiency and environmental sustainability.

Biochemical technologies like AD remain among the most economically favorable WtE options, particularly for the organically rich municipal waste typical in Saudi Arabia. AD processes have low capital and operational costs (0.1–0.14 USD/ton and 0.2–0.28 USD/ton respectively) and are well suited for high-moisture food waste stream [34]. Larger facilities

with capacities into the millions of tons/years can be established with moderate capital investments (e.g., about 59.36 million USD for a facility processing 22.11 Mt/year) and deliver energy with lower complexity and minimal labor requirements compared to thermal systems (total O&M cost of 9595 USD/ton) [10]. Despite these strengths, AD feasibility is sensitive to feedstock quality, collection logistics, and seasonal waste generation variations, which affect both production consistency and economic returns. For agricultural crop residues, AD systems need approximately 10.67 million USD, providing moderate electricity generation and lower emissions compared to combustion [10]. Additional systems for sewage treatment require around 9 million USD, while those handling animal waste are estimated at 7.12 million USD, primarily focusing on cow and camel manure [10].

Chemical WtE conversion via transesterification offers another economically viable pathway for lipid-rich waste, with initial investments ranging from 200,000 to 500,000 USD and conversion efficiencies up to 98%, alongside O&M costs of about 35 to 70 USD/ton [34]. While not as financially robust as large pyrolysis or gasification systems, this method's economics depend heavily on the availability and reliability of lipid-rich feedstocks, and costs associated with catalyst supply and processing infrastructure. RDF production is also cost-competitive for mixed waste, with low capital and operation costs (7.5–11.3 USD/ton and 0.3–0.55 USD/ton respectively) [34]. This method is effective in managing various waste types, including paper, plastics, and textiles, thereby representing an efficient strategy for energy recovery from MSW. RDF bridges waste management and energy recovery, with economic performance sensitive to waste sorting efficiency and local demand for fuel.

Economic assessments from previous studies reinforce the importance of conducting sensitivity analyses to capture uncertainties due to external variables. Stochastic cost–benefit frameworks show that collection fees and electricity prices significantly influence the overall cost–benefit ratio of WtE facilities, and under certain conditions WtE plants can sustain themselves financially without subsidies [168]. This aligns with the financial feasibility modelling for Saudi WTE plants, which identifies capacity factors and waste throughput as major determinants of investment viability [167]. Furthermore, international reviews highlight that countries seeking cost-effective and environmentally sustainable WtE pathways often require supportive governmental policies, economic incentives, and private sector involvement to overcome barriers and ensure long-term viability [169].

Overall, while baseline economic data in Table 17 provide a foundation for comparison, the actual feasibility of WtE technologies in Saudi Arabia is contingent on key economic variables. Prices for electricity and fuels, supportive incentives (e.g., tariffs, subsidies, gate fees), and localized manufacturing and labor costs can all shift project outcomes significantly. Plasma gasification leads with substantial revenue potential but requires significant investment, making it suitable for large-scale applications. Conventional gasification provides economic feasibility for smaller facilities but may be less appealing at larger scales due to higher costs. Pyrolysis demonstrates strong adaptability and profitability, particularly for plastics and biomass. AD serves as a cost-effective and sustainable method limited to organic waste. Transesterification offers an efficient route for producing biodiesel, while RDF production stands out as a practical means of managing mixed waste.

6. WtE Implementation in Saudi Arabia: Status, Benefits, and Challenges

6.1. WtE Initiatives

Saudi Arabia is currently facing significant challenges in managing the increasing volumes of MSW generated due to rapid urbanization, population growth, and evolving consumption patterns, particularly in major cities like Riyadh, Jeddah, and Dammam [25,31,166]. Estimates indicate that per capita MSW generation of 1.4–1.75 kg per person daily, leading to an annual total exceeding 16 million tons [2,14]. Historically, most

of this waste has ended up in landfills, which raises critical environmental and health concerns [54]. To mitigate these issues and align with Vision 2030, the Kingdom has initiated several WtE projects aimed at converting MSW into electricity, heat, and RDF.

6.2. Current Status of WtE Projects

6.2.1. Operational and Planned WtE Facilities

The development of WtE facilities in Saudi Arabia primarily emphasizes the conversion of waste into usable fuel rather than electricity generation. Notably, the Saudi Investment Recycling Company (SIRC) operates facilities that process approximately 3 million tons of MSW annually, focusing on high-energy waste streams, particularly plastics, which constitute about 23% of the total MSW. SIRC successfully converts 35% of this waste into RDF while recycling additional fractions [170,171]. This operation alleviates landfill pressure, substitutes conventional fuels, and aligns with the circular economy goals outlined in Vision 2030 [172]. While electricity generation capabilities are currently limited, several thermal WtE plants are in planning stages to directly generate electricity from MSW. For instance, the proposed Jeddah WtE Plant aims to process approximately 3500 tons of waste daily, with an expected output of around 100 MW of electricity [173]. This initiative is designed to minimize landfill usage and reduce associated GHG emissions while enhancing the city's electricity supply [173].

Similarly, the Riyadh WtE Plant is anticipated to manage about 1.3 million tons of MSW each year, generating roughly 200 MW of electricity for the capital area. Both projects will be implemented under public–private partnerships (PPP) and will utilize advanced thermal WtE technologies to optimize energy recovery, aligning with the Kingdom's goals for energy diversification and sustainability [173]. In line with these efforts, the Saudi government has initiated the King Abdullah City of Atomic and Renewable Energy (KACARE) program, aimed at establishing renewable energy sources through science, research, and industry [33]. The plans include generating 54 GW of energy from various renewable sources, including nuclear, wind, solar, and WtE facilities [33]. Table 18 provides an overview of the major operational and planned WtE projects in the Kingdom.

Table 18. Current status of WtE projects in KSA.

Project Name	City	Type of WtE	Waste Type	Capacity	Estimated Cost, $	Status	Key Features and Goals	Ref.
Saudi Investment Recycling Waste-to-Fuel Facility	Multiple Cities (Riyadh, Jeddah, Dammam)	RDF production (Energy Feedstock)	MSW, primarily focusing on plastic waste, which constitutes 23% of total MSW	3 million t/year (RDF)	Approx. $300 million	Operational	Converts MSW into RDF for industrial use, alleviating landfill pressure and supporting a circular economy aligned Vision 2030.	[170–172]
Jeddah WtE Plant	Jeddah	Thermal WtE (Electricity Generation)	Mixed MSW (Organics, plastics, paper, glass)	3500 t/day (100 MW)	Approx. $200 million	Planned	A major project to convert MSW into electricity, targeting a reduction in fossil fuel use and emissions.	[173]

Table 18. *Cont.*

Project Name	City	Type of WtE	Waste Type	Capacity	Estimated Cost, $	Status	Key Features and Goals	Ref.
Riyadh WtE Plant	Riyadh	Thermal WtE (Electricity Generation)	Mixed MSW (Household and light industrial waste)	1.3 million t/year (200 MW)	Approx. $400 million	Planned	A large-scale project expected to significantly reduce CO_2 emissions by 200 thousand tons, with investment from ACWA power, enhancing the capital's electricity supply.	[173]

6.2.2. Advantages of WtE Projects in KSA

WtE projects in Saudi Arabia offer numerous advantages. Environmentally, they help reduce reliance on landfills and lower CH_4 emissions, thereby enhancing air quality and promoting better public health outcomes [170,172]. In terms of energy, thermal WtE plants and the production of RDF contribute additional sources of electricity and fuel, aiding in the diversification of the Kingdom's energy mix [171]. Economically, these projects are expected to draw both domestic and international investments, while also creating job opportunities in waste collection, plant operation, and maintenance sectors [170,171].

6.2.3. Challenges of WtE Projects in KSA

Despite their benefits, WtE projects face several challenges in Saudi Arabia. The diverse composition of MSW, characterized by high organic content and fluctuating calorific values, can hinder energy recovery efficiency [170,171]. Additionally, the high capital and operational costs present financial hurdles, necessitating the adaptation of advanced WtE technologies to local waste characteristics and climate conditions for optimal effectiveness [171]. Furthermore, a robust regulatory framework, including feed-in tariffs and gate fees, is essential to ensure the economic feasibility of these projects.

7. Role of WtE in Saudi Vision 2030

Saudi Vision 2030 is a national strategic framework designed to transform the Kingdom of Saudi Arabia into a global investment powerhouse and a modern, diversified economy. It is built around three main pillars, including a vibrant society, a thriving economy, and an ambitious nation [27,77]. While Vision 2030 highlights economic diversification through sectors such as tourism and infrastructure, it also emphasizes environmental sustainability and responsible resource management as key elements of long-term development. In line with this, effective solid waste management and the adoption of WtE technologies are increasingly recognized for their potential to support these national goals.

A vibrant society under Vision 2030 seeks to improve the quality of life for residents, which includes managing environmental impacts from rapid urbanization and large population inflows. For example, the Kingdom's plans to increase annual Umrah visitors from 8 million to 30 million and to accommodate over 6 million Hajj pilgrims by 2030 require expanded infrastructure and services to manage the resulting MSW [53]. WtE technologies help reduce the volume of waste sent to landfills by converting it into energy, which in turn lowers harmful emissions such as CH_4 and other pollutants that negatively affect air quality and public health [53]. Research on WtE potential in Saudi Arabia shows that integrated

waste management systems, including WtE, can significantly reduce landfill dependency and generate meaningful amounts of electricity from MSW, thereby contributing to cleaner and healthier urban environments. For instance, modeling studies estimate that WtE systems using MSW could generate hundreds of megawatts of power by 2030, illustrating how WtE can contribute both to environmental sustainability and to the improved living conditions envisioned [62].

Under the thriving economy pillar, Vision 2030 places strong emphasis on economic diversification and building new sectors beyond oil. The WtE sector aligns with this goal by creating new industries and employment opportunities tied to waste processing, energy generation, and circular economic activities. National strategies for solid waste management anticipate significant contributions from WtE and other waste valorization pathways as part of a broader resource-efficient economy [62]. Market analysis indicates that Saudi Arabia's planned waste treatment framework, including recycling, composting, and waste conversion technologies, can support economic growth and attract both public and private investments [62]. In this model, enhanced WtE infrastructure contributes not only to local energy supplies but also creates value streams from previously unused waste materials, fostering new jobs in operations, engineering, and environmental services. These developments support the Kingdom's efforts to diversify its economy and reduce dependency on oil revenues, in line with Vision 2030's broader economic objectives [62].

The ambitious nation pillar of Vision 2030 focuses on sustainability, innovation, and Saudi Arabia's integration into global economic and environmental frameworks. WtE plays a role in this by supporting circular economy principles and reducing GHG emissions, objectives that align with international commitments such as the United Nations Sustainable Development Goals (SDGs) [174]. For example, the capture of landfill CH_4 and its use in energy production can supplement the Kingdom's energy mix while reducing methane emissions, a potent GHG. A recent study quantifying CH_4 emission from Saudi landfills projected that capturing this gas could generate up to 1299 GWh per year from biomethane alone, highlighting the potential of waste-related energy sources to contribute to broader energy and climate strategies [54,174]. By integrating landfill gas capture and WtE into national waste management policies, Saudi Arabia strengthens its capacity to manage environmental challenges and advance toward clean energy targets, demonstrating leadership in sustainable development while advancing the nation's long-term vision [54].

In the context of SWM, two SDGs are notably relevant, including SDG 7, which focuses on ensuring access to affordable, reliable, sustainable, and modern energy for all, and SDG 12, which promotes sustainable consumption and production patterns [175]. The report affirms that KSA is dedicated to enhancing energy security and has initiated several large-scale projects aimed at developing a renewable energy sector that prioritizes environmental sustainability. Although KSA currently lacks comprehensive regulations for managing MSW, the Kingdom is actively working on establishing environmental sustainability laws and practices to safeguard its natural resources, thereby integrating WtE strategies into its development framework.

8. Future Work and Research Directions in WtE Development in KSA

Future research on WtE in Saudi Arabia should adopt integrated, system-oriented approaches that simultaneously consider environmental, economic, and regional aspects of MSW management. Recent trends indicate a shift towards sustainability assessments, LCA, optimization, and environmental impact evaluations, highlighting the need for holistic frameworks that extend beyond energy recovery. Such approaches should align WtE system performance with landfill diversion strategies and national sustainability objectives, particularly under the framework of Saudi Vision 2030.

A significant direction emerging from keyword clustering analysis is the increasing interest in advanced thermochemical technologies, such as pyrolysis, gasification, and plasma gasification, alongside RDF, as shown in Figure 8. Research in these areas necessitates prioritization of techno-economic optimization and scalability under local conditions, considering feedstock variability, energy demand, and economic feasibility. Biochemical conversion pathways, especially AD, biomethanation, and biogas production, remain central to WtE advancements due to the high OFMSW in Saudi Arabia. Future studies should integrate AD with energy efficiency, exergy analyses, and renewable energy systems, exploring co-digestion strategies, nutrient recovery, and biogas upgrading to enhance overall system performance.

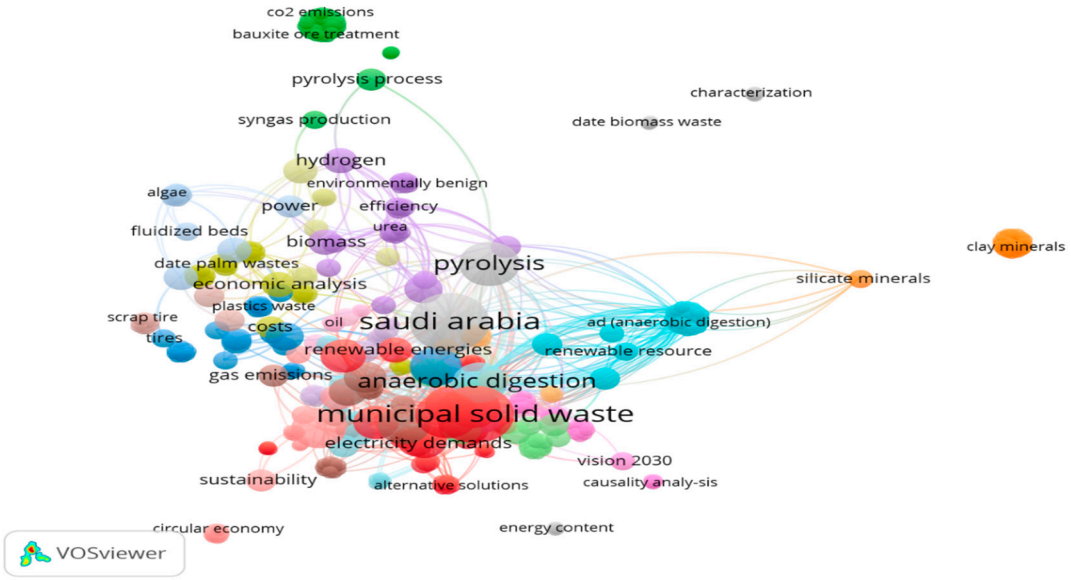


Figure 8. Author keyword co-occurrence network and research clusters related to WtE studies in KSA.

Advanced thermochemical technologies, including pyrolysis, gasification, plasma gasification, and RDF, are receiving growing attention due to their potential to convert complex waste streams into energy and valuable byproducts. However, while these technologies are promising, their technical maturity in Saudi Arabia requires careful assessment. Future studies should focus on techno-economic optimization and scalability under local conditions, taking into account feedstock variability, seasonal surges in waste generation during Hajj and Umrah, energy demand, and capital and operational costs. Plasma gasification, for example, demonstrates high efficiency in converting plastics and mixed waste into syngas, but large-scale implementation depends on comprehensive pilot-scale evaluations and lifecycle environmental impact studies [48].

Biochemical pathways such as AD, biomethanation, and biogas production remain central to WtE development in Saudi Arabia due to the high organic fraction in municipal waste. Optimizing AD for high-moisture food waste, co-digestion strategies, nutrient recovery, and biogas upgrading can enhance energy yields and system efficiency. Integrating AD with energy and exergy analyses, renewable energy systems, and site-specific operational strategies will improve overall performance and support circular economy objectives [167]. Additionally, waste-based biorefineries and biofuel production present a critical research avenue. Studies on converting MSW into biodiesel, pyrolysis oil, methanol, and waste fats demonstrate promising outcomes, but further process simulation and techno-economic analyses are required to identify scalable and economically viable configurations suitable for Saudi waste streams [52,167].

Research should incorporate GIS-based site selection, regional demand modeling, and localized case studies to account for variations in waste generation due to industrial activity, tourism, and religious events such as Hajj and Umrah. This approach allows for optimized technology selection, improved infrastructure investment, and cost-effective facility siting [54]. Moreover, integration with climate change mitigation strategies is essential. Future studies should examine carbon capture and storage (CCS), CH_4 capture from landfills, GHG mitigation modeling, and stakeholder engagement to ensure long-term sustainability, social acceptance, and alignment with national and international environmental objectives [176]. The integration of waste-based biorefineries and biofuel production signals another critical research avenue. Increasing attention to biodiesel, biofuels, pyrolysis oil, methanol, and waste fats as alternative energy carriers calls for further exploration using process simulations and fluidized bed reactors to identify scalable and economically viable biorefinery configurations.

Finally, economic, technical, and policy considerations must be addressed comprehensively. The successful implementation of WtE technologies in Saudi Arabia depends not only on waste characteristics but also on capital and operational costs, technological complexity, labor skill availability, and geographical suitability. Recent studies emphasize that the effectiveness of waste management legislation, including the 2021 Waste Management Law, is often constrained by practical implementation barriers such as limited enforcement capacity, weak monitoring mechanisms, and insufficient coordination between national and municipal authorities [177]. In addition, public awareness and community acceptance play a decisive role in WtE deployment, as concerns related to emissions, health impacts, and facility siting have been identified as major sources of local opposition when stakeholder engagement is limited [177].

Stakeholder involvement is therefore critical for advancing WtE projects. Active participation of local communities, municipalities, and the private sector can reduce social resistance and improve project acceptance. From an investment perspective, private-sector participation strongly depends on the clarity, stability, and predictability of regulatory framework [177]. Previous research highlights that the absence of supportive instruments such as feed-in tariffs, gate fees, long-term power purchase agreements, and transparent risk-sharing mechanisms can significantly limit private investment in WtE infrastructure, particularly in emerging and developing economies [177]. Policy and regulatory frameworks, including landfill pricing, disposal fees, and incentives, play a key role in promoting WtE competitiveness. Experiences from other countries indicate that well-designed policies enhance WtE adoption, while poorly structured regulations may encourage illegal dumping rather than sustainable waste management practices. By integrating these technological, environmental, economic, spatial, and policy dimensions, future WtE research can provide actionable, context-specific strategies to advance Saudi Arabia's transition toward a sustainable, circular, and energy-efficient waste management system aligned with Vision 2030 goals.

9. Comparison of WtE Technologies in Saudi Arabia

The MSW in Saudi Arabia varies widely in composition, moisture content, and quantity across regions and seasons. For this reason, choosing an appropriate WtE technology cannot rely on a single option. A clear comparison is required to understand which technologies are most suitable under different waste characteristics, economic conditions, and environmental priorities [27–29]. Table 19 presents a summarized comparison of WtE technologies based on findings from previous studies conducted in Saudi Arabia.

Table 19. Comparison of WtE technologies applicable to MSW in KSA.

Technology	Suitable Waste Type	Energy Recovery	Economic Feasibility	Environmental Impact	Technology Maturity	Suitable Scale	Ref.
Incineration	Mixed MSW, plastics, paper	High (20–30% efficiency; up to 2073 MW nationality)	High capital cost	Strong landfill reduction; air emissions.	Very high	Large cities	[5,19,31,50,62,65]
Gasification	Dry, high-calorific waste	High (Syngas production)	High capital cost	Lower emissions than incineration.	Medium-high	Medium-large	[57,65,90]
Plasma Gasification	Mixed waste	Very high waste reduction	Very high cost	Very low residues	Medium	Large	[46,58,80]
Pyrolysis	Plastics, biomass, RDF	Medium-high (oil and gas products)	Medium to high	Lower emissions	Medium	Small-medium	[125–127]
AD	Organic-rich waste	Medium (up to 2.99 TWh/year)	Low operating cost	Excellent GHG reduction	High	Small-medium	[87,136,154]
Transesterification	Lipid-rich waste (FOG)	Very high (about 98% efficiency)	High net economic gain	Strong CH_4 reduction	Medium	Small-medium	[33,163]
RDF	Mixed MSW after sorting	Indirect (Fuel substitution)	Low to medium	Supports landfill diversion	High	Medium-large	[29,33,65]

The comparison in Table 19 shows that no single WtE technology can fully manage Saudi Arabia's MSW on its own. Anaerobic digestion performs best for organic waste, which forms the largest fraction of Saudi MSW (about 37–57%). It has low operating costs and provides strong environmental benefits, especially in reducing methane emissions [87,154]. Transesterification is highly efficient for lipid-rich waste and generates strong economic returns, but its use is limited by the availability of suitable feedstock and the need for proper waste separation [33,163]. Therefore, it is best used as a complementary technology alongside AD.

Among thermochemical technologies, incineration is the most mature and suitable for large cities. Studies in Riyadh, Jeddah, Dammam, and the Eastern Province show that incineration can generate significant electricity while reducing landfill use [31,50,62,65]. However, high capital costs, emission control requirements, and public acceptance remain important challenges [5,19]. Gasification and plasma gasification offer higher flexibility but require stable waste quality and strong financial support [19,43]. Pyrolysis and RDF systems provide flexible options for plastic-rich and mixed waste streams. RDF production is especially important because it improves the performance of thermal WtE systems and supports integrated waste management strategies [127].

Overall, the comparison confirms that an integrated WtE system, combining biochemical, chemical, and thermochemical technologies, is the most suitable approach for Saudi Arabia. This integrated strategy allows better use of different waste fractions, improves energy recovery, reduces environmental impacts, and supports the goals of Vision 2030.

10. Conclusions

This comprehensive review highlights the urgent need for innovative WtE solutions in Saudi Arabia, where MSW generation is escalating, currently generates more than 16 million tons annually. This volume corresponds to a per capita waste generation of approximately 1.4 to 1.75 kg per day, primarily composed of organic materials (37% to 57%), followed by paper (11% to 28%), and plastics (5% to 36%). The variability in waste composition is particularly pronounced during seasonal peaks, such as Hajj and Ramadan, where daily waste can surge to 4500 tons in Makkah, necessitating adaptive WtE strategies.

AD is identified as the most appropriate technology for the organically rich fraction of Saudi MSW. National-scale analyses indicate a recoverable energy potential of up to 2.99 TWh/year, while city-level applications demonstrate outputs of 164.5 GWh/year in Makkah and approximately 15.64 MW of continuous power in Madinah. AD consistently shows the lowest operational costs among WtE options, ranging between 0.1 and 0.14 USD/ton, and offers substantial environmental benefits through landfill diversion and CH_4 mitigation. However, its scalability is constrained by feedstock quality, source separation efficiency, space availability, and sensitivity to operational disturbances, particularly in dense urban environments.

Chemical WtE conversion via transesterification emerges as a highly efficient and economically attractive pathway for lipid-rich waste streams. Case studies demonstrate conversion efficiencies approaching 98%, with large-scale applications capable of processing around 64,000 t/year of waste oils and fats. This pathway can generate approximately 244.2 GWh of electricity annually and deliver net economic gains of about 76.5 million SAR per year. These results confirm that transesterification plays a strategic complementary role by valorizing waste fractions unsuitable for AD or direct combustion, although its deployment depends heavily on reliable collection systems and feedstock purity. It complements AD by valorizing fats and oils while reducing CH_4 emissions, reinforcing the principles of a circular economy.

Thermochemical WtE technologies are essential for managing high-calorific and heterogeneous waste fractions, particularly plastics and paper. Incineration demonstrates strong robustness and capacity to process mixed MSW, achieving waste volume reductions of up to 90–95% and offering a national electricity generation potential of approx. 2073 MW. Gasification and plasma gasification provide greater flexibility by producing syngas and reducing waste volumes by up to 99%, but they require significantly higher capital investments and stable energy markets to remain economically viable. Pyrolysis shows strong adaptability, particularly for plastics and biomass, with several Saudi case studies reporting short payback periods and attractive internal rates of return when feedstock supply and product markets are secured.

RDF production represents a cost-effective intermediate solution for mixed MSW, with low capital and operational costs and the ability to divert large quantities of waste from landfills. RDF supports industrial energy demand and enhances system flexibility, particularly when integrated with recycling and thermal WtE pathways.

The analysis reveals clear trade-offs between capital intensity, operational complexity, and energy recovery potential. Capital-intensive technologies such as plasma gasification and large-scale incineration deliver high energy outputs but are sensitive to electricity tariffs and investment conditions. In contrast, AD, RDF, and transesterification offer lower-cost, feedstock-specific solutions with strong environmental performance but limited applicability to specific waste fractions. Overall feasibility is strongly influenced by waste throughput, capacity factors, gate fees, and electricity pricing.

Overall, the evidence from Saudi-based studies confirms that no single WtE technology can independently address the Kingdom's MSW challenge. The most effective strategy is an integrated WtE framework that combines AD for organic waste, transesterification for lipid-rich fractions, thermochemical technologies for high-calorific residues, and RDF for mixed waste streams. Such an approach can substantially reduce GHG emissions. When aligned with Saudi Vision 2030, this integrated WtE system offers a technically feasible, economically rational, and environmentally sustainable pathway for advancing circular economy objectives and long-term waste management resilience in the Kingdom.

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Abbreviations

The following abbreviations are used in this manuscript:

WtE	Waste-to-Energy
MSW	Municipal Solid Waste
MPW	Municipal Plastic Waste
KSA	Kingdom of Saudi Arabia
GHG	Greenhouse gases
Bbl/d	Barrels per day
Gg	Gigagram
AD	Anaerobic digestion
RDF	Refuse-derived fuel
LCV	Lower calorific value
MRF	Material recovery facilities
LCA	Life cycle assessment
H_2	Hydrogen
CO	Carbon monoxide
PTP	Plasma treatment project
CH_4	Methane
CO_2	Carbon dioxide
DFB	Dual fluidized-bed
DPF	Date palm fronds
ASR	Automotive shredder residue
OFMSW	Organic fraction of municipal solid waste
C	Carbon
N	Nitrogen
NO_X	Nitrogen oxides
HC	Hydrocarbon
DB	Biodiesel Blend
FAME	Fatty acid methyl easter
FFA	Free fatty acids
SIRO	Saudi Investment Recycling Company
PPP	Public–private partnerships
KACARE	King Abdullah City of Atomic and Renewable Energy
SDGs	Sustainable development goals

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