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Article

Harnessing Renewable Energy from Municipal Solid Waste: Challenges and Opportunities in the Eastern Province of Saudi Arabia

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Abstract: Rapid urbanization in Saudi Arabia has significantly increased municipal solid waste (MSW) generation, intensified environmental pressures and complicated sustainable waste management. Despite ongoing national initiatives aligned with Vision 2030, systematic integration of waste-to-energy (WtE) approaches remains limited, particularly in the Eastern Province. This study investigates the major challenges associated with MSW management in the region, including population growth, inadequate collection and segregation practices, limited recycling infrastructure, and the environmental and socio-economic impacts of current disposal methods. A mixed-methods approach was adopted, incorporating a comprehensive literature review, analysis of recent datasets from the General Authority of Statistics (GASTAT), and projections of per capita waste generation (kg/person/day) from 2022 to 2060 under various urban growth scenarios. The study also examined existing MSW management practices and evaluated their alignment with global benchmarks. Comparative case studies from Sweden, Japan, Egypt, and selected Arab countries were analyzed to identify successful WtE and circular-economy strategies and to determine their applicability to the Saudi context. Findings reveal significant gaps in waste segregation, recycling rates, and technological adoption, alongside promising opportunities to harness renewable energy from MSW through scalable thermal and biological conversion pathways. The study provides policy recommendations to strengthen regulatory frameworks, enhance resource recovery, and integrate WtE solutions into municipal planning. The insights aim to support decision-makers in advancing sustainable MSW management and accelerating the transition toward a circular economy in the Eastern Province

Keywords: municipal solid waste management; renewable energy; waste-to-energy; circular economy; urbanization; 3Rs.

1. Introduction

The global population has now reached about 8.2 billion as of 2025, with cities home to approximately 45% of all people worldwide (UN, 2025a). By mid-century, the total population is projected to approach 9.8 billion, while the share of the global population living in urban areas is expected to reach roughly 68% by 2050 (UN, 2025b). Similarly, in 1950, only 20% of the global population lived in cities, but by 2025 cities host nearly half of humanity (UN, 2025b). These demographic and spatial transitions intensify pressure on urban infrastructure, services, and waste management systems, underscoring the urgency of sustainable urban planning and Waste-to-Energy (WtE) strategies. In the Saudi Arabia, and particularly in the Eastern Province, a region characterized by high urban density, extensive industrial activity, and strategic energy infrastructure, where annual MSW production has risen to 1.8 billion metric tons, with 1.5 to 1.8 kg per person per day of waste generation (Labib et al., 2021a; Labib et al., 2023). Transforming MSW from a disposal problem into a resource through WtE and circular-economy approaches aligns with national sustainability objectives (including Vision 2030), offers pathways to reduce landfill reliance, and can contribute to local energy supply diversification. However, realizing the WtE potential of MSW requires understanding regional waste composition, technological suitability, economic feasibility, governance arrangements, and social acceptance. These factors vary greatly by context, and strategies that succeed in temperate, high-income settings do not automatically transfer to Gulf urban systems (Moya et al., 2017). This study investigates the challenges and opportunities for harnessing renewable energy from MSW in the Eastern Province of Saudi Arabia. It integrates demographic and waste-generation trends with a review of WtE technologies, environmental trade-offs, and governance lessons drawn from international and regional studies. The aim is to provide evidence-based recommendations for policy makers and municipal authorities on technology choices, regulatory design, and integration of WtE within a broader circular economy strategy (Rimi and Lawal, 2020).

Municipal solid waste (MSW) is broadly classified into organic and inorganic components**.** Organic waste primarily consists of biodegradable materials such as food waste, while inorganic waste includes plastics, minerals, and textiles (Uyar and Hayber, 2025; Anjum et al., 2016). Among these, organic waste presents significant opportunities for resource recovery; for instance, its treatment through anaerobic digestion has considerable potential to generate renewable energy in the form of biogas (Samavedam et al., 2025). In addition, emerging research emphasizes the role of adaptive, data-driven systems in improving energy efficiency under dynamic conditions (Samaei and Riffat, 2025). Technologies such as cognitive digital twins enable real-time monitoring and optimization, enhancing system performance and resilience. Applying similar approaches to waste management could improve waste-to-energy (WtE) efficiency by optimizing feedstock use, process control, and energy recovery despite variations in waste composition. Numerous socioeconomic factors in Saudi Arabia have led to a massive amount of food waste (Mu'azu et al., 2019). The management of waste through practices such as landfilling (dumping) is the root problem causing a substantial impact on the environment, e.g., as evidenced by greenhouse gas (GHG) emissions (Anjum et al., 2016). Recently, the Saudi Arabia has become aware of this problem. Unfortunately, there are no clear policies or strategies concerning WM. Government support and commitment are required to ensure the continuous improvement of quality management. More recent studies suggest that while food (organic) waste remains the largest fraction of MSW in Saudi Arabia, its share continues to show variability depending on region and urban context. Food waste accounts for approximately 50.57% of MSW in municipal areas (Baig et al., 2022), with food waste estimated at 40–51%, paper at 12–28%, cardboard specifically at ~7%, and plastics in a range of 5–17%.

Recent studies show that MSW composition in Saudi Arabia varies significantly across regions, which has important implications for WtE planning and the circular economy. A localized assessment conducted in Al-Ahsa in the Eastern Region reported a more balanced distribution of waste types, with paper and cardboard comprising approximately 17.1%, food waste 14.7%, plastics 13.8%, wood 13.5%, metals 11.4%, and glass 10.8% of the overall waste stream (Elmosaad et al., 2023). These values contrast with the national estimates by Nizami et al. (2015), who identified food waste as the dominant fraction (50.6%), followed by plastics (17.4%), paper (11.9%), and cardboard and other waste (6.7%). This contrast underscores the substantial regional variability in MSW composition across the country.

Such variability is particularly relevant for WtE technologies, as each waste category yields different calorific values, influencing the feasibility and efficiency of specific energy recovery pathways. Table 1 compares the energy content of major MSW components with conventional fossil fuels. Food waste and green yard waste, for instance, have relatively low calorific values, making them more suitable for biological conversion processes such as anaerobic digestion. In contrast, plastics, rubber, leather, and textiles demonstrate higher calorific values, supporting thermal conversion options such as pyrolysis or RDF-based combustion.

Table 1. Energy content of municipal solid waste components compared with fossil fuels (adapted from Nizami et al., 2015)

Type of Waste	Energy Content (MJ/kg)	Fossil Fuel	Energy Content (MJ/kg)
Mixed paper	15.82	Coal	28.61
Mixed food waste	5.58	Fuel oil	42.57
Mixed green yard waste	6.28	Natural gas	55.14
Mixed plastic	32.57	–	–
Rubber	26.06	–	–
Leather	18.61	–	–
Textiles	18.98	–	–
Demolition softwood	16.98	–	–
Waste hardwood	15.12	–	–

Based on these calorific values and the national waste composition reported by (Nizami et al. 2015), Table 2 summarizes the projected energy potential from key WE technologies. Anaerobic digestion of food waste offers the highest overall energy potential (30,760 TJ), while pyrolysis of plastics yields the highest calorific return per ton of waste. RDF combustion of mixed waste streams also presents a viable pathway for electricity generation at scale. Together, these findings illustrate the technical feasibility of deploying integrated WtE systems as part of Saudi Arabia's broader sustainability and energy diversification strategies.

Table 2. Energy potential of major WtE technologies based on MSW composition in Saudi Arabia (Nizami et al., 2015)

Technology	Waste Stream Used	Waste Used (Mt)	Energy Potential (TJ)	Electricity Generation (TWh)
Anaerobic digestion (biogas)	Food waste (50.6%)	7.7	30,760	2.99
Pyrolysis (fuel oil)	Plastic (17.4%)	2.7	85,190	1.03
RDF combustion	Mixed waste (26.3%)	4.0	35,008	1.55
Recycling	Glass (2.9%) and metals (2.7%)	0.9	44,593	–

To strengthen the theoretical foundation of this study within the context of Vision 2030 and the CE, greater attention is given to the role of thermal conversion technologies, particularly pyrolysis, in transforming MSW and biomass into RE and value-added products. Pyrolysis is widely recognized as an efficient thermochemical process that converts waste into useful outputs such as bio-oil, biochar, and syngas, thereby supporting both energy recovery and resource efficiency within WtE systems. For example, (Kar et al. 2023) demonstrate that the fast pyrolysis of mixed biomass, including tea bush, walnut shell, and pine cone, can significantly enhance energy yield while producing high-value biofuels. Beyond energy production, recent research also highlights the potential of waste materials to be utilized in innovative applications. (Cuce et al. 2025) show that hazelnut shell waste can be successfully incorporated into advanced thermal insulation materials, illustrating how waste can be transformed into valuable construction resources within a CE framework.

In addition to thermal conversion, expanding the framework to include alternative and hybrid RE systems further enhances the depth of the analysis. Hybrid systems, such as floating solar technologies, offer promising solutions for improving energy efficiency, optimizing land use, and supporting integrated energy systems (Tian et al. 2025). (Solomin et al. 2021) highlight that hybrid floating solar plants can be combined with other RE sources to improve system performance and sustainability. This is particularly relevant in the Arab region, where countries such as Egypt are increasingly adopting integrated approaches that combine RE technologies with MSW management strategies to address rising energy demand and environmental challenges (Salah et al., 2022). These developments reflect broader energy–environment interactions, where MSW management, RE generation, and climate policy are closely interconnected.

Overall, integrating pyrolysis-based WtE processes, biomass-derived material applications, and hybrid RE systems provides a more comprehensive and forward-looking framework that aligns with Vision 2030 objectives. It reinforces the idea that MSW should not be viewed solely as an environmental burden, but as a valuable resource that can contribute to RE generation, material innovation, and sustainable urban development.

In addition, (Abdullah et al. 2022) highlight that effective waste management is closely linked to progress toward the UN Sustainable Development Goals (SDGs), particularly SDG 11 (sustainable cities), SDG 12 (responsible consumption and production), and SDG 13 (climate action). Their analysis further notes that G20 nations, including Saudi Arabia, account for 60% of the world's population, 80% of global economic output, and 75% of greenhouse gas emissions. This reinforces the central role that Saudi Arabia's waste management and renewable energy initiatives play in meeting international sustainability commitments. Figure 1 presents the Fragile States Index (FSI) scores for G20 countries, as reported by the Economist Intelligence Unit and the FSI 2021. The results show that Saudi Arabia falls within the fourth quartile, indicating comparatively weaker performance relative to other G20 members. This position underscores the significance of examining the country's waste management challenges, as addressing them can support policy development and enhance municipal and governmental sector resilience.

Country	Headline Finding	Food Loss & Waste	Sustainable Agriculture	Nutritional Challenges
Argentina	2nd Quartile	2nd Quartile	3rd Quartile	3rd Quartile
Australia	1st Quartile	2nd Quartile	1st Quartile	1st Quartile
Brazil	4th Quartile	4th Quartile	3rd Quartile	3rd Quartile
Canada	1st Quartile	1st Quartile	1st Quartile	1st Quartile
China	3rd Quartile	3rd Quartile	4th Quartile	2nd Quartile
France	1st Quartile	2nd Quartile	2nd Quartile	2nd Quartile
Germany	1st Quartile	1st Quartile	1st Quartile	2nd Quartile
India	4th Quartile	3rd Quartile	4th Quartile	4th Quartile
Indonesia	4th Quartile	4th Quartile	4th Quartile	4th Quartile
Italy	2nd Quartile	1st Quartile	3rd Quartile	3rd Quartile
Japan	1st Quartile	1st Quartile	1st Quartile	1st Quartile
Mexico	4th Quartile	4th Quartile	2nd Quartile	4th Quartile
Russia	3rd Quartile	3rd Quartile	4th Quartile	3rd Quartile
Saudi Arabia	4th Quartile	4th Quartile	4th Quartile	4th Quartile
South Africa	3rd Quartile	3rd Quartile	2nd Quartile	4th Quartile
South Korea	2nd Quartile	3rd Quartile	1st Quartile	2nd Quartile
Turkey	3rd Quartile	4th Quartile	3rd Quartile	2nd Quartile
United Kingdom	2nd Quartile	2nd Quartile	2nd Quartile	1st Quartile
United States	3rd Quartile	3rd Quartile	4th Quartile	3rd Quartile

FSI Performance Key

- 1st Quartile (Best Performing)
- 2nd Quartile
- 3rd Quartile
- 4th Quartile (Worst Performing)

Figure 1. The G20 countries FSI results

According to (Alzahrani 2019), Saudi Arabia has one of the highest population growth rates globally, estimated at 3.4%. Combined with rapid economic expansion driven by the oil and gas sector, this growth contributes to rising consumption levels and an associated increase in municipal solid waste generation. Currently, MSW is managed primarily by local municipalities, with landfilling being the dominant disposal method. However, reliance on landfills is widely recognized as unsustainable due to environmental, spatial, and economic constraints. As noted by (Al Blooshi et al. 2016), substantial improvements in waste management systems are urgently needed to ensure that Saudi Arabia can meet its future waste handling and sustainability goals.

This study addresses the challenges of MSWM in the Eastern Province, where rapid urbanization, population growth, and infrastructure limitations continue to strain existing systems. The research aims to assess current MSWM practices, identify key issues such as rising waste volumes and continued reliance on landfilling, and evaluate the suitability of renewable energy and WtE technologies such as incineration, anaerobic digestion, and refuse-derived fuel within the context of Saudi Arabia's Vision

2030. Using a mixed-method approach, the study incorporates updated waste and population data from the GASTAT and employs quantitative forecasting to project waste generation trends from 2022 to 2060, addressing gaps in earlier studies that relied on outdated estimates. Through reviewing local practices, regional challenges, and international case studies, the research provides evidence-based recommendations to support policymakers in advancing a more sustainable, energy-efficient, and circular waste management framework for the Eastern Province.

Despite the growing body of literature on MSWM and WtE technologies, limited attention has been given to long-term projections at the regional scale in Saudi Arabia, particularly in the Eastern Province. Many existing studies rely on short-term estimates or outdated datasets, with limited consideration of how demographic growth and urban expansion will influence future waste generation patterns. In addition, there is a lack of context-specific analysis linking waste characteristics to appropriate WtE technologies. This study addresses these gaps by providing updated projections extending to 2060 and by examining how WtE solutions can be realistically integrated within the regional planning context.

2. Literature review

Solid waste refers to discarded materials generated from households, commercial establishments, institutions, and public spaces, and its management typically falls under municipal responsibilities for collection, transportation, treatment, and disposal (Labib et al., 2023). SWM is inherently complex, requiring reliable information on waste generation rates, composition, and forecasting. Waste generation levels are influenced by multiple socioeconomic and demographic factors, including income, population density, consumption patterns, and urbanization (Cherian and Jacob, 2012; Kaza et al., 2018). Effective SWM encompasses a series of interconnected processes, from generation and storage to collection, transfer, treatment, recycling, and final disposal, guided by environmental, economic, legal, and public health principles. Municipal solid waste is heterogeneous in nature, and its composition varies according to local cultural, climatic, and geographic conditions (Othman, 2002; Ferronato and Torretta, 2019). This literature review is organized into four main categories: (1) current MSWM practices in the Eastern Province, Saudi Arabia, (2) international case studies of renewable energy and WtE implementation, (3) key challenges associated with SWM, and (4) policy recommendations for Saudi Arabia and regional stakeholders.

2.1. Current MSWM Practices in the Eastern Province

Saudi Arabia's waste management sector is administratively structured under three core national entities. The Ministry of Environment, Water, and Agriculture oversees national strategies for environmental protection, water security, and agricultural sustainability. The National Center for Waste Management (MAWANI), established in 2020 under Council of Ministers Order No. 457, regulates and supervises all WM activities and promotes the transition toward a circular economy (MAWANI, 2023). The National Center for Environmental Compliance (MWAN) ensures regulatory enforcement, licensing, and environmental monitoring. The Saudi Investment Recycling Company (SIRC), a subsidiary of the Public Investment Fund, leads industrial-scale waste recovery and recycling initiatives, aiming to divert up to 85% of waste from landfills by 2035. SIRC develops and operates recycling facilities for plastics, construction and demolition waste, metals, and organics, aligning with Vision 2030's environmental goals. In the Dammam Metropolitan Area, which includes Dammam, Dhahran, and Khobar municipalities coordinate with NCWM and SIRC to initiate waste collection contracts, develop recycling infrastructure, and prepare procurement tenders to expand WtE capacity (International Trade Administration, 2022). Recent studies highlight that the Eastern Province generates one of the highest per-capita MSW rates in the Saudi Arabia, driven by rapid population growth, industrial expansion (notably petrochemicals), and high consumption levels (Hadidi et al., 2020). While landfilling remains the primary disposal method, national plans aim to scale recycling and WtE technologies to reduce dependence on land disposal and mitigate environmental impacts.

2.2. Successful Case Studies of Renewable Energy and WtE

Place illustrations (figures, tables, drawings, and photographs) throughout the paper at the places where they are first discussed in the text, rather than at the end of the paper. Number illustrations sequentially (but number tables separately). Place the illustration numbers and caption under the illustration in 10 ptfont.All figures and tables should be cited in the main text as Figure 1, Table 1, etc.

2.2.1. Case Study 1 Sweden

Sweden is globally recognized for its advanced waste management and WtE systems. Less than 1%

of its municipal waste is landfilled, with 99% redirected to recycling or energy recovery (Tsuyama, 2020). This achievement stems from comprehensive legislation, strong municipal autonomy, financial incentives, and a long-standing culture of recycling. Cities such as Uppsala and Borås utilize integrated WtE plants that convert waste into electricity, district heating, and biogas (Ishola and Tilli, 2019; Rajendran et al., 2013). Policy innovations such as a tax reduction on repair services, consumer incentives like HandM's textile return program, and a robust bottle-deposit system have contributed to high material recovery rates (Hinde, 2020). Sweden has also invested in low-carbon incineration and extensive biogas upgrading technologies to decrease GHG emissions. According to (Akhator et al. 2016), Sweden generated approximately 2.0 TWh of electricity from 5.7 million tonnes of MSW in 2014, demonstrating high efficiency in energy recovery. Data from (Avfall Sverige 2022) show a continuous increase in WtE capacity from 1985 to 2022 (Figure 2), both in terms of waste processed and energy generated. Sweden's integrated approach has served as a benchmark for several countries exploring WtE as part of sustainable waste management (Akhator et al., 2016; Ferronato and Torretta, 2019).

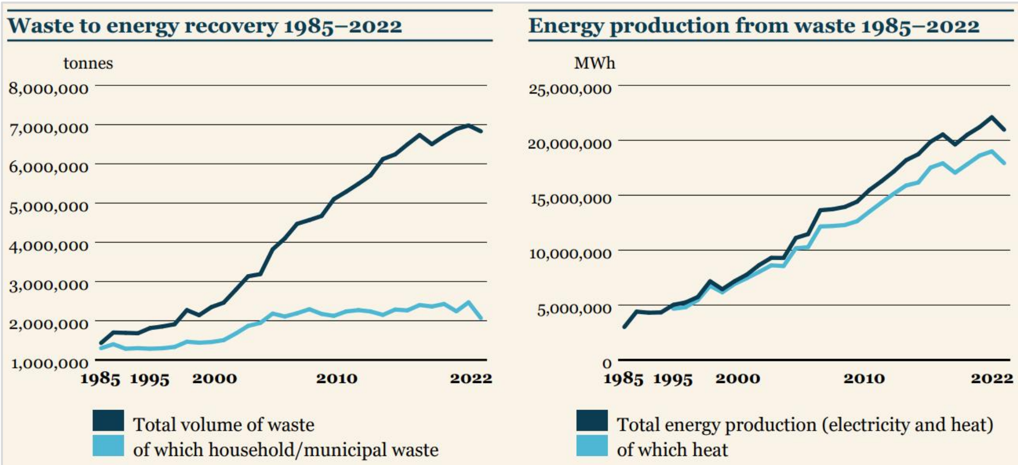


Figure 2. WTE recovery from 1985 to 2022 (left) and energy generation (right) (Source: Avfall Sverige, 2022)

2.2.2. Case Study 2 Japan

Japan is widely regarded as a global leader in efficient and sustainable waste management due to its long-standing emphasis on resource conservation and integrated policy frameworks (Moshkal et al., 2024). Central to Japan's national strategy is the Sound Material-Cycle Society Plan, which advances the 3Rs: Reduce, Reuse, and Recycle, while encouraging active public participation and extended producer responsibility (Silva et al., 2017; Hotta and Aoki-Suzuki, 2014). Japan has one of the highest municipal solid-waste incineration rates globally, with thermal treatment serving as a cornerstone of its WtE system to minimize landfill use and recover energy (Wahyudi and Novitasari, 2018). Several municipalities have demonstrated outstanding performance through large-scale source-separation programs. For example, Yokohama achieved a 38% reduction in household waste within ten years by expanding recycling categories and conducting continuous community engagement campaigns (Hotta and Aoki-Suzuki, 2014).

Recent studies further highlight Japan's advancements in high-efficiency incineration, flue-gas cleaning, and smart WtE plant management, which collectively reduce emissions while improving electricity and heat recovery (Brotosusilo and Nabila, 2020; Moshkal et al., 2024). Emerging research also documents Japan's increasing investment in circular-economy initiatives, including biodegradable plastics, decentralized composting, and digital monitoring systems for waste tracking (Kojima, 2022; Yoshida, 2022). Despite its progress, Japan continues to face challenges such as aging infrastructure, rising waste volumes, and the need to further expand recycling markets. Ongoing policy reforms and technological innovations aim to address these gaps, ensuring that Japan remains a leader in sustainable materials management and WtE development (Moshkal et al., 2024). Figure 3 compares municipal incineration rates across major industrialized nations (Wahyudi and Novitasari, 2018).

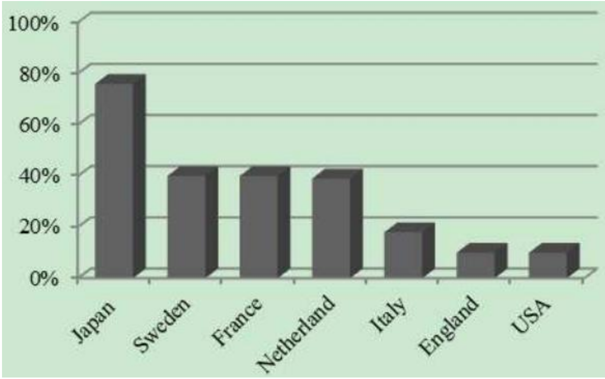


Figure 3. Comparison of incineration rates across various countries (Source: Wahyudi and Novitasari, 2018).

2.2.3. Case Study 3 Egypt and Arab Countries

Egypt and several Arab countries have recently intensified efforts to reform their WM and renewable energy systems, recognizing both sectors as critical to national sustainability agendas. (Salah et al. 2022) emphasize that although Egypt possesses substantial renewable energy resources, ranking 31st globally in solar energy utilization. However, its potential remains significantly underexploited. Fossil fuels continue to dominate approximately 90% of Egypt's electricity generation, contributing to nearly 250 million tons of CO_2 emissions annually, while renewable sources account for only 9% (Salah et al., 2022). The authors highlight that advanced renewable (biomass, geothermal, wave, nuclear) currently represent a mere 0.16% of the energy mix. To enhance energy security and meet SDGs, the study recommends expanding private-sector participation, improving manufacturing localization, and leveraging high solar intensity zones along the Red Sea and Upper Egypt.

Egypt has set ambitious targets to generate 42% of its electricity from renewable energy by 2030 and has integrated WtE projects into national WM strategies (Salah et al., 2022). The country aims to convert approximately 4.2 million tons of MSW into energy by 2035 (Salah et al., 2022). However, implementation is slowed by regulatory bottlenecks, unclear feed-in tariffs, weak incentives for investors, and inadequate coordination across agencies. To address these constraints, (Salah et al. 2022) propose two strategic pathways for achieving Egypt's 2035 objectives, stressing the need for modernizing grid infrastructure, introducing transparent pricing mechanisms, and strengthening policy frameworks to reduce emissions and align with international climate commitments such as the Kyoto Protocol.

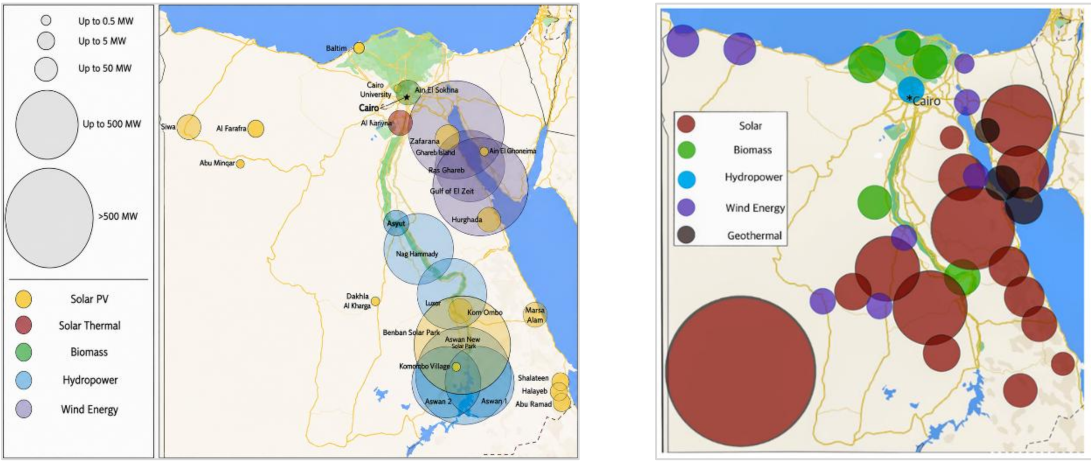
Other scholars have identified similar challenges across Arab countries. For example, (Hemidat et al. 2022) note that Egypt's MSW systems continue to face issues related to informal waste collection, limited recycling capacity, and low public awareness, all of which hinder the availability of high-quality feedstock for WtE processes. In Jordan, (Abu Qdais et al. 2019) demonstrate that WtE initiatives are technically feasible; however, their implementation depends on stronger legislative frameworks and more reliable data on waste composition. Similarly, in Oman, (Qazi et al. 2021) highlight ongoing efforts to shift from landfilling to energy recovery, driven by high per capita waste generation and the need for more sustainable WM practices. Comparable developments are also observed in the UAE and Qatar, where large-scale WtE facilities, such as the Dubai WtE plant one of the largest globally reflect a growing regional shift toward Circular Economy (CE) principles and decarbonization (Shareefdeen et al., 2020; Abdallah et al., 2018; Al-Moftah et al., 2025).

Overall, the literature indicates that, despite the significant potential for RE and WtE across the Arab region, progress remains constrained by fragmented governance structures, financial uncertainties, infrastructure limitations, and inconsistent enforcement of environmental regulations. Addressing these challenges requires strengthening regulatory clarity, improving inter-agency coordination, enhancing private-sector participation, and investing in integrated WM infrastructure. These insights provide valuable lessons for Saudi Arabia and the Eastern Province, where similar opportunities exist to align WtE development with Vision 2030 objectives and broader CE goals.

To provide a clearer comparison of international experiences, Table 3 summarizes the key WtE strategies, strengths, challenges, and their relevance to Saudi Arabia. This comparison is further supported by Figure 4, which illustrates the distribution of current RE projects, existing facilities, and potential development locations in Egypt, highlighting the country's ongoing transition toward more integrated RE and WtE systems (Salah et al., 2022).

Table 3. Summary of the key WtE strategies, strengths, challenges, and their relevance to Saudi Arabia.

Country	Main WtE/MSWM Approach	Key Strengths	Main Challenges	Relevance to Saudi Arabia
Sweden	Highly integrated MSWM system combining recycling, WtE, district heating, and biogas production	Extremely low landfill use (less than 1%); strong regulatory framework; high public participation; advanced WtE technologies; effective economic incentives such as deposit-refund systems	Requires long-term institutional stability, advanced infrastructure, and sustained public engagement	Demonstrates how integrated policies, strong governance, and WtE technologies can significantly reduce landfill dependence and enhance energy recovery (Tsuyama, 2020; Ishola and Tilli, 2019; Rajendran et al., 2013; Hinde, 2020; Avfall Sverige, 2022)
Japan	Resource-efficient MSWM system focused on the 3Rs, strict waste segregation, and thermal treatment (incineration with energy recovery)	High level of waste sorting; strong public awareness; advanced incineration and emission control technologies; well-established policy framework	Aging infrastructure; increasing waste volumes; need to further strengthen recycling markets	Highlights the importance of behavioral change, source segregation, and policy-driven systems in improving MSWM performance and reducing landfill reliance (Hottaand Aoki-Suzuki, 2014; Wahyudi and Novitasari, 2018; Moshkal et al., 2024; Brotosusilo and Nabila, 2020)
Egypt	Emerging integration of RE expansion with WtE and WM reforms	Ambitious RE targets (42% by 2030); plans to convert ~4.2 million tons of MSW into energy; increasing policy focus on sustainability	Regulatory challenges; limited coordination; weak investment incentives; infrastructure and data gaps; low recycling rates	Provides relevant insights for Saudi Arabia on integrating RE with MSWM, improving governance, and strengthening private-sector involvement (Salah et al., 2022; Hemidat et al., 2022; Al-Flaiyeh, 2022)
Saudi Arabia (current)	Predominantly landfill-based MSWM with increasing focus on recycling, WtE, and CE under Vision 2030	Strong policy direction; institutional support (MAWANI, MWAN, SIRC); high potential for resource recovery and WtE expansion	Continued reliance on landfilling; limited waste segregation; low recycling participation; infrastructure gaps; need for stronger coordination and public awareness	Represents a transitional stage where lessons from international case studies can support the development of more integrated and sustainable MSWM systems in the Eastern Province (Hadidi et al., 2020; International Trade Administration, 2022; Abdullah et al., 2022; Labib et al., 2023)



A B

Figure 4. A: depicts current renewable energy projects and plants; B: shows potential locations for renewable energy (Salah et al., 2022)

（Al-Flaiyeh 2022）provides an in-depth review of WtE technologies, analyzing their current trends, technical feasibility, and environmental implications amidst the growing challenge of MSW due to rapid urbanization. The study highlights the increasing adoption of WtE in developed nations as a dual solution for sustainable WM and energy production, effectively contributing to energy security while reducing reliance on fossil fuels. It emphasizes the role of WtE in mitigating GHG emissions, particularly methane from landfills, thus offering a significant environmental benefit. In contrast, the paper explores the potential for applying anaerobic digestion and other decentralized WtE methods in developing countries, where infrastructure and financial resources may be limited. The research reports a notable conversion efficiency of approximately 45.3%, capable of producing around 507 kWh of electricity per metric ton of processed waste, underscoring the energy-generating potential of WtE systems. Furthermore, the study addresses the socio-economic advantages of WtE projects, including emission reductions, the conservation of land resources, and the creation of green jobs across the value chain from waste collection to energy production. The author stresses the importance of integrated WM strategies, where recycling, energy recovery, and material reuse complement each other. To support the wider adoption of WtE technologies, the conclusion calls for active government involvement through policy frameworks, tax incentives, subsidies, and public-private partnerships. Figure 5 in the study provides a comparative illustration of electric power generation from MSW across eight Arab countries, revealing disparities in adoption and highlighting the potential for regional collaboration and investment in WtE infrastructure.

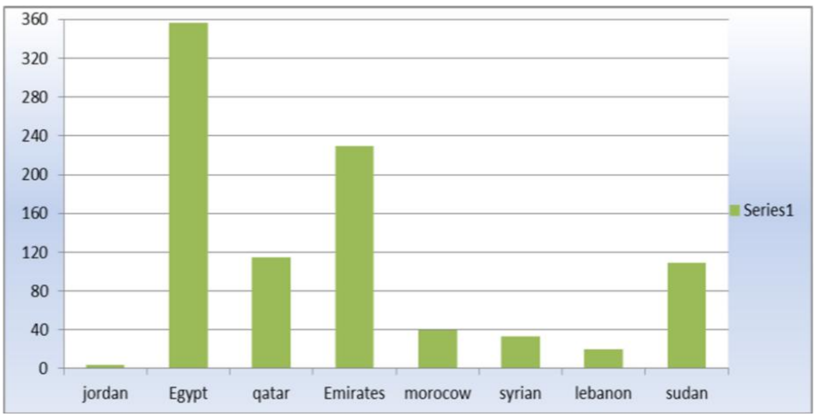


Figure 5. Electric power generation from MSW in eight Arab countries (Source: Al-Flaiyeh, 2022)

2.3. Environmental and Social Challenges Resulting from Inadequate MSWM in the Eastern Province, Saudi Arabia

Rapid urbanization and population growth across Saudi Arabia have intensified the strain on MSWM systems, particularly in the Eastern Province. (Labib et al. 2023) emphasize that poorly managed MSW contributes to a wide range of environmental and social problems, including air pollution, GHG emissions, ecological degradation, public health risks, aesthetic deterioration, odor nuisances, and reduced property values. Similar findings in other Gulf countries demonstrate that inadequate landfill practices and limited recycling capacity exacerbate soil and groundwater contamination, posing long-term sustainability concerns (Siddiqi et al., 2021; Sabarathinam et al., 2025). Improper MSWM is also strongly linked to increased disease transmission, higher healthcare expenditures, and broader socio-economic burdens (Anjum et al., 2016). In Saudi Arabia, open dumping and the overreliance on landfilling remain critical issues due to infrastructure gaps, limited waste segregation, and low public participation in recycling initiatives (Alghuson and Alghuried, 2025). Furthermore, studies conducted in rapidly growing Saudi cities show that rising waste volumes, driven by population expansion, economic diversification, and changing consumption patterns, are outpacing the capacity of existing MSWM systems.

A key study by (Labib et al. 2021a), focusing on Dammam, provides insight into household behaviors influencing MSW sorting and recycling. The authors developed a behavioral model (Figure 6) incorporating internal factors such as attitudes, awareness, and perceived behavioral control and external factors including social influence, market incentives, and government facilitators. Their findings reveal that positive attitudes toward recycling and strong environmental awareness significantly increase willingness to sort waste. Market-based incentives, supportive policies, and publicly available recycling facilities also play an important role in encouraging household participation, especially in low-income communities. Although social influence contributes to recycling behaviors, its effect is comparatively weaker than institutional and psychological drivers. More recent studies in the Gulf context support these conclusions. (Al-Sari' and Haritash 2024) report that MSWM effectiveness in Arab countries remains hindered by limited waste segregation at the source, insufficient recycling infrastructure, and low community engagement. In Saudi Arabia, the MWAN has underscored the need for greater public participation and improved institutional coordination to reduce environmental burdens associated with landfill dependency (MWAN, 2023).

Collectively, the literature indicates that the environmental and social impacts of inadequate MSWM in the Eastern Province are multi-dimensional, reflecting infrastructure limitations, behavioral challenges, and governance gaps. Addressing these issues requires a comprehensive approach that integrates community awareness, economic incentives, strengthened regulations, and investment in WtE and recycling technologies aligned with Vision 2030.

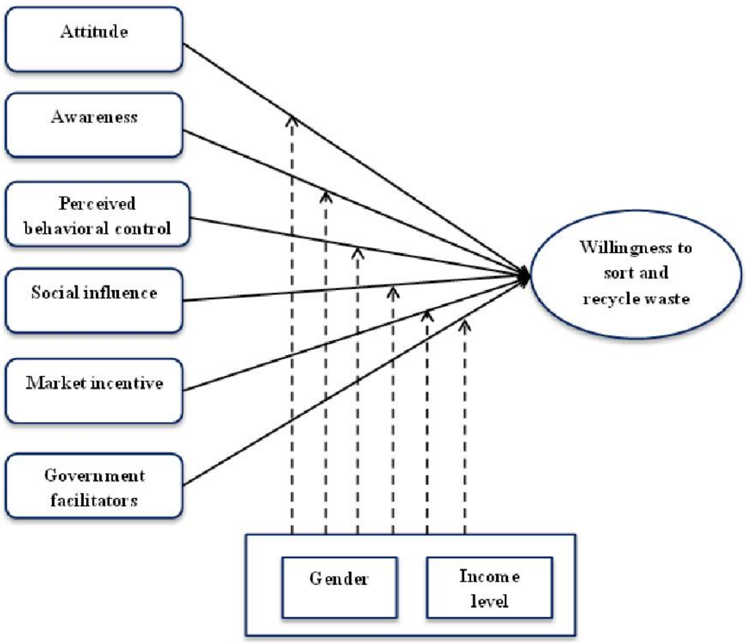


Figure 6. Model of intension of waste sorting (Labib et al., 2021a)

2.4. Recommendations for policymakers and stakeholders

Given the increasing volume of MSW in Saudi Arabia and the associated environmental, social, and economic pressures, transitioning toward a more sustainable WM framework is both urgent and necessary. Previous studies, including(Hadidi et al. 2020), highlight that existing waste infrastructure is insufficient to manage rising waste volumes, while also emphasizing the potential of MSW as a resource for energy generation and value-added products. In this context, integrating the 3Rs strategy with WtE technologies provides a practical pathway for reducing landfill dependence, conserving resources, and improving environmental outcomes.

Several studies offer valuable insights into how such strategies can be implemented. For instance, (Nizami et al. 2017) and (Miandad et al. 2016) demonstrate the potential of converting organic waste into biofuels and biogas, highlighting the role of WtE in renewable energy production. (Rehan et al. 2017) further contribute by proposing integrated WM systems that combine waste reduction, recycling, and energy recovery to improve overall system efficiency. In addition, (Khan et al. 2017) emphasize the importance of recycling and the recovery of value-added products, supporting the transition toward a circular economy.

Despite these opportunities, MSW management in the Eastern Province continues to face several challenges, including limited adoption of advanced treatment technologies and a continued reliance on landfill disposal. Strengthening the role of the private sector through investment and job creation, along with adopting modern waste treatment technologies, can significantly improve system performance. The integration of the 3Rs framework, as illustrated in Figure 7, further supports waste reduction and resource recovery efforts. Overall, these approaches align with Saudi Arabia's Vision 2030 objectives, promoting a circular economy and more sustainable WM practices (Abdullah et al., 2022).

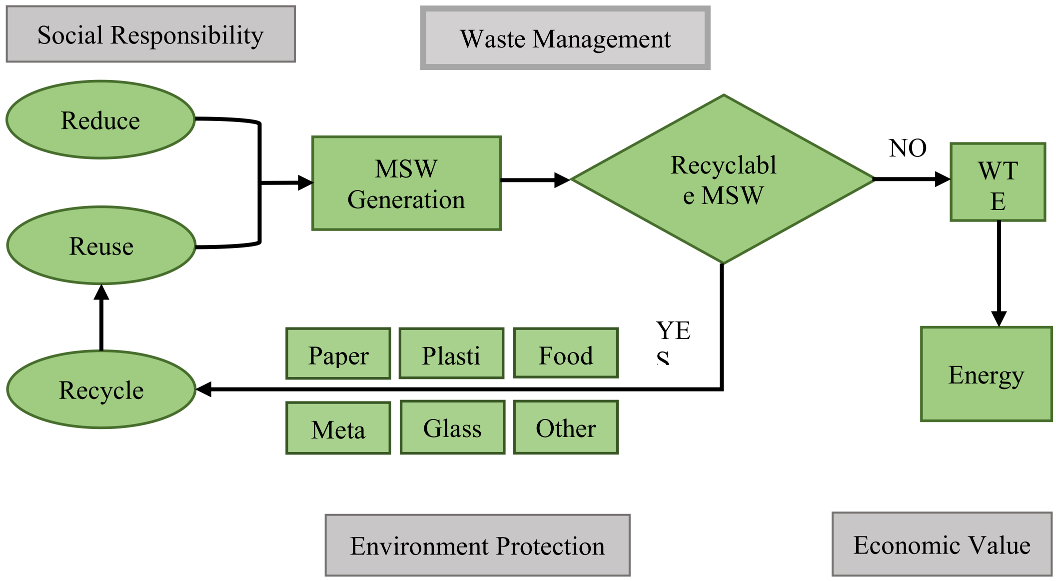


Figure 7. Conceptual framework integrating the 3Rs with WtE processes, adapted from (Hadidi et al. 2020).

The conceptual framework presented in Figure 7 illustrates the integration of the 3Rs with WtE processes. This framework also supports the interpretation of future waste management pathways, including business-as-usual, gradual improvement, and circular economy scenarios. Islamic policy encourages people to reuse and recycle products, to motivate individuals to recycle, reuse, and convert food waste into animal feeds. Moreover, private charity sectors have been established to recycle and reuse food waste. The Saudi Food Bank was established in 2010 by Mr. Abdulrahman Al Rajhi, and it is also called "Ita'am." This bank was ranked as the best food bank in the GCC in 2020 (Saudi Food Bank, 2020). According to the Ministry of Municipal and Rural Affairs (2017), challenges of waste collection in the Saudi Arabia is critical because of extensive communal skip containers. This collection method leads to mixing waste types that obstruct their treatment. The requirement of separation in the cities is essential, as is the need to implement a national policy of extended producer responsibility (EPR) because of the lack of experience and knowledge. The EPR would result in individual motivation for handling waste generation.

The recommendations of the Ministry of Municipal and Rural Affairs (2017) are the following:

1. Awareness campaigns must be introduced before and in parallel with the technical changes.
2. Skip containers, which have wheels, should be replaced with smaller containers similar to the well-known 1.1 m3 containers, robust steel containers without wheels emptied by front end- or side-loading vehicles.
3. Individual bins and containers must be placed in new buildings.
4. Covering waste with a lid is essential; foot pedal opening devices and "lid-in-the-lid" solutions

must be considered.

5. Single-family buildings should participate in a two-fraction door-to-door collection. Also, the daily collection will be costly, so weekly or twice-weekly residual waste collections will be appropriate, along with a weekly collection of dry recyclables, depending on the volume of garbage.

6. Litter bins in public areas should be established to break the habit of literally tossing trash on the street or in the park.

Case Study 1:

To harness renewable energy from MSW and emulate Sweden's WM and WTE model, policymakers in the Eastern Province should develop a comprehensive WM policy that integrates recycling, energy recovery, and waste minimization, similar to Sweden's holistic approach (Tsuyama, 2020). Implementing economic instruments, such as tax reforms to incentivize repairs and recycling, along with a bottle deposit scheme to promote effective waste sorting, can enhance participation (Hinde, 2020). Investing in advanced WtE technologies, akin to those in Uppsala and Borås that convert waste into biogas, electricity, and heat, will provide dual benefits of WM and renewable energy generation, including achieving zero-energy constructions (Ishola and Tilli, 2019; Rajendran et al., 2013; Raheem et al., 2026). Public awareness campaigns and incentives for participation can foster a culture of sustainability, while collaboration with local stakeholders and learning from global best practices can lead to innovative solutions (Akhator et al., 2016). Finally, establishing performance metrics and leveraging data for decision-making will ensure accountability and adaptability in WM strategies (Avfall Sverige, 2022).

Case Study 2:

To improve WM in the Eastern Province, policymakers can adopt strategies from Japan's effective and sustainable WM system. This system is supported by the Sound Material-Cycle Society Plan, which emphasizes the 3Rs and encourages public involvement (Moshkal et al., 2024; Silva et al., 2017). Japan primarily utilizes thermal treatment methods, particularly incineration, to minimize landfill waste while generating energy (Wahyudi and Novitasari, 2018). Cities like Yokohama and Kamakura have successfully implemented intensive source separation and recycling initiatives (Hotta and Aoki-Suzuki, 2014). Japan's achievements in waste reduction are driven by its focus on sustainable materials management, advanced technologies, and robust government support (Hotta and Aoki-Suzuki, 2014). Despite its successes, Japan continues to face challenges and invests in innovative technologies and environmental awareness campaigns to further strengthen its WM system (Moshkal et al., 2024; Brotosusilo and Nabila, 2020). Adopting these principles could significantly improve WM practices in Eastern Province.

Case Study 3:

To enhance renewable energy and WM in the Eastern Province, policymakers can learn from Egypt's experiences as outlined by (Salah et al. 2022) and (Al-Flaiyeh 2022). (Salah et al. 2022) emphasize Egypt's significant renewable energy potential, noting that despite ranking 31st in solar energy use, renewables contribute only 0.16% to electricity generation, with fossil fuels making up 90% of the mix. They recommend attracting private investment in renewables and developing hydropower agreements to achieve a goal of 42% renewable electricity by 2030. (Al-Flaiyeh 2022) highlights the increasing adoption of WTE technologies in developed Arab nations, which help mitigate GHG while providing energy. The study suggests that decentralized WTE methods, such as anaerobic digestion, could be effective in developing countries, achieving around 45.3% energy conversion efficiency. Both studies advocate for strong government support through policies and partnerships to facilitate the adoption of renewable energy and WTE systems, positioning Eastern Province for improved sustainability.

In summary, as sorting and infrastructure is the critical concern in Saudi Arabia the findings indicated the desire of households to sort garbage is favorably influenced by attitudes, social influence, perceived behavioral control, market incentives, awareness, and government facilitators (Labib et al., 2021a). It is suggested that households sort their garbage on a daily basis. The willingness to sort and recycle is not greatly influenced by social factors (Labib et al., 2021a; Labib et al., 2021b). Also, taken in consideration the case studies discuss it included solutions of the challenges faced that are similar to Saudi Arabia condition this will help in modifying current policy of WM in Saudi Arabia and specifically in Eastern Province. Nonetheless, the Ministry of Municipal and Rural Affairs (2017) recommendations had been included in this research to show the willingness of government and action taken to align with Vision 2030. Moreover, Islamic policy motivates the 3Rs therefore, habits can change through implementing new policies.

3. Methodology

3.1. Study Setting

This study focuses on the Eastern Province of Saudi Arabia, as illustrated in Figure 8. The province covers approximately 672,522 km² and is home to around 5.1 million residents, making it one of the most rapidly growing and economically significant regions in the country (Jamal et al., 2020). According to the most recent release from the GASTAT (2023), Saudi Arabia's total population is 32,175,225, of which 58.4% are Saudi nationals and 41.6% are non-Saudis. The Eastern Province population provides the demographic foundation for estimating MSW generation and forecasting future trends within the region. Over the past decade, the number of registered vehicles has surged from 2.97 million in 2011 to 5.27 million in 2017, reflecting accelerated urbanization and economic growth (Jamal et al., 2020). This expansion has introduced new environmental pressures, including increased waste generation, pollution, and growing demands on municipal services. As the hub of Saudi Arabia's oil, gas, and petrochemical industries, the Eastern Province is home to major industrial complexes and the headquarters of Saudi Aramco, the world's largest oil company. The continuous industrial expansion not only drives population growth but also contributes to complex waste streams, including MSW, industrial by-products, and construction waste.

The province also has a highly diverse population, with a substantial proportion of expatriate workers from various cultural backgrounds. This demographic heterogeneity results in varied lifestyle patterns, consumption behaviors, and waste generation characteristics, contributing to the complexity of MSWM systems in the region. These combined factors: rapid urbanization, industrial intensification, population growth, and social diversity, make the Eastern Province a critical case for examining the challenges and opportunities associated with municipal solid waste management. The region's evolving economic landscape and alignment with Saudi Arabia's Vision 2030 reforms further underscore the need for sustainable, data-driven MSWM strategies to reduce landfill dependence and promote resource recovery.

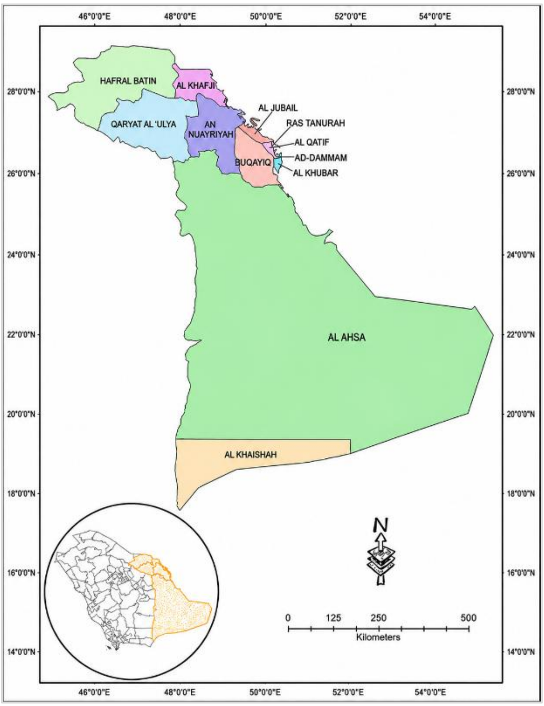


Figure 8. The Eastern Province of Saudi Arabia showing its 12 cities (Jamal et al., 2020)

3.2. Data Sources and Reliability

This study adopts a desktop research design using a mixed-methods approach, integrating both qualitative and quantitative analyses. The qualitative component draws from peer-reviewed literature accessed primarily through Google Scholar, including journal articles, institutional reports, and studies focusing on MSWM, urbanization trends, and WtE developments in Saudi Arabia and comparable international contexts. Particular emphasis is placed on literature pertaining to Saudi Arabia, and more specifically, the Eastern Province, to situate the findings within the regional context. To ensure validity and reliability, the study relies on official government datasets from national public agencies, chiefly:

- The GASTAT, and
- The MAWANI.

These institutions provide authoritative demographic, environmental, and waste-related data. An inquiry for updated data was submitted via the GASTAT platform, after which an email confirmation and inquiry code were received. GASTAT subsequently made the requested datasets available for download through their portal using the provided code, ensuring access to the most current population and MSW figures.

3.3. Quantitative Analysis

The quantitative component analyzes:

- Historical and current MSW generation trends,
- Per capita waste generation rates (PPPD), and
- Population growth projections.

Data were organized and analyzed using Microsoft Excel, where calculations, tabulations, and graphical trend analyses were performed.

3.3.1. Forecasting Approach

This study builds upon the MSW forecasting approach developed by (Hadidi et al. 2020), which estimated population growth and waste generation trends using 2010 as a baseline year. Their analysis projected that MSW generation would increase from approximately 2,110 thousand tons in 2010 to 3,545 thousand tons by 2030, primarily driven by demographic expansion and evolving consumption patterns. In the present study, this framework is extended using updated datasets from the GASTAT (2023) to estimate MSW generation in the Eastern Province over the period 2022–2060. By shifting from earlier baseline estimates to more recent data, the analysis addresses temporal limitations in previous studies and provides a longer-term perspective to support infrastructure planning, recycling strategies, and potential WtE development.

To enhance the policy relevance of the analysis, a scenario-based approach is adopted to capture potential variations in future MSW generation. Three development pathways are considered: the Business-As-Usual (BAU) scenario, in which current waste generation trends continue; a moderate improvement scenario, reflecting gradual progress in recycling and MSWM practices in line with Vision 2030; and an advanced CE scenario, where higher levels of waste segregation and WtE integration are achieved (Birgen et al., 2024; Setyono et al., 2025). Although these scenarios are not modeled as separate simulations, they provide a structured framework for understanding how different policy, technological, and behavioral changes may influence future MSW generation patterns (Birgen et al., 2024; Setyono et al., 2025). To project MSW generation from 2022 to 2060, this study adopts a per capita waste generation rate of 1.24 kg/person/day, based on (Radwan et al. 2021), as a baseline reference. While this assumption simplifies long-term dynamics, it is intentionally used to provide a consistent and transparent basis for assessing the impact of population growth on future MSW generation. However, recognizing the limitations of assuming a constant rate over an extended period, the scenario-based framework allows for a more realistic interpretation of how MSW generation may evolve under different policy and management conditions.

In this context, the BAU scenario assumes no significant changes in consumption or MSWM practices, while the moderate improvement scenario reflects gradual reductions in per capita MSW generation driven by increased recycling, improved waste segregation, and enhanced public awareness under Vision 2030. The CE scenario represents a more advanced pathway, where stronger policy implementation, wider adoption of WtE technologies, and more efficient resource utilization led to a more substantial reduction in MSW generation and landfill dependency. Overall, this approach moves beyond a fixed projection and provides a more realistic and policy-relevant assessment of future MSW trends. Rather than predicting exact quantities, the analysis illustrates the scale, range, and direction of potential MSW generation under different development pathways, particularly in the context of Vision 2030 and evolving MSWM strategies.

A new schematic diagram has been developed and incorporated into the methodology section to visually represent the proposed MSW management framework. Figure 9 illustrates the conceptual structure of the three MSW management scenarios, highlighting the progressive integration of the 3Rs principle from BAU to CE pathways. The figure also demonstrates how the 3Rs framework is combined with WtE processes across three development scenarios: BAU, moderate improvement, and CE. This visual representation clarifies how WM practices can progressively transition from conventional disposal methods toward more sustainable and resource-efficient systems. Furthermore, the diagram is an original contribution of this study, specifically designed to reflect the regional context of the Eastern Province and align with the strategic objectives of Vision 2030.

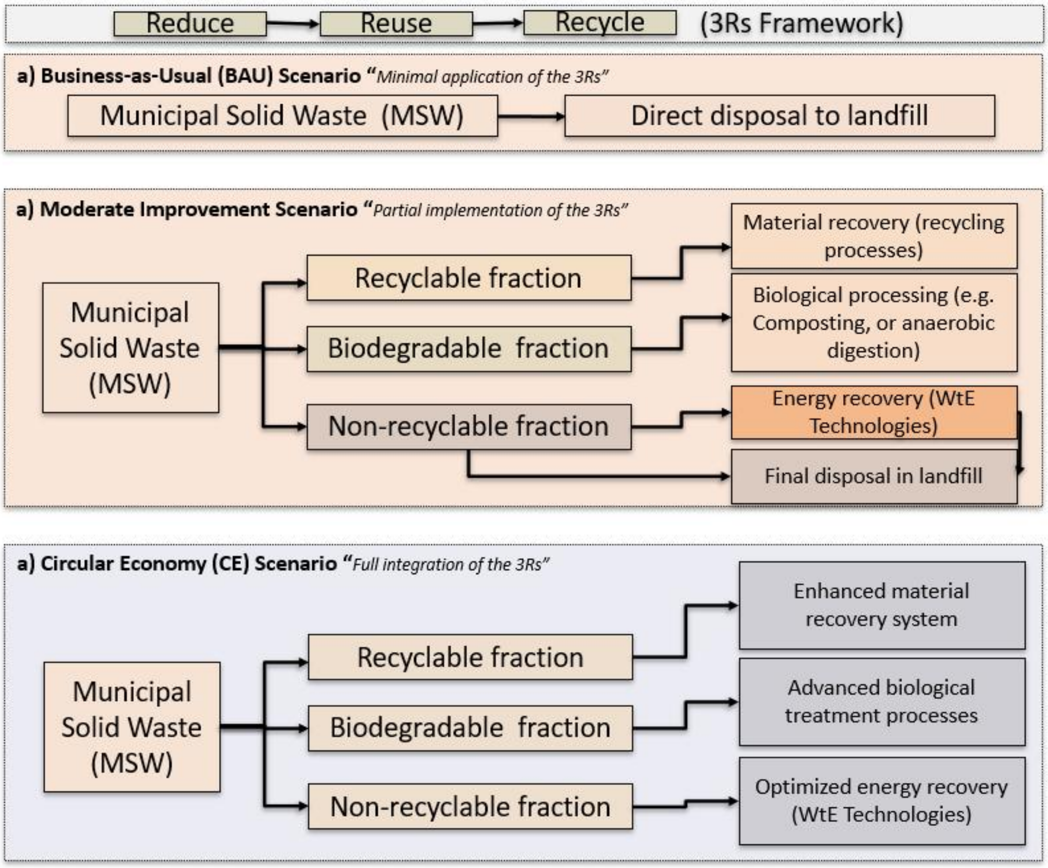


Figure 9*.* The Conceptual structure of the three MSWM scenarios, highlighting the progressive integration of the 3Rs principle from BAU to CE Scenarios.

4. Results and Discussion

According to GASTAT (2023), the Eastern Province is experiencing a population growth rate of 3.375%, highlighting its rapid urbanization compared to global trends. This continued growth is putting increasing pressure on municipal infrastructure, especially municipal solid waste management (MSWM). The population is not evenly distributed across the region, with Al Dammam holding the largest share (30%), followed by Al Ahsa (22%), Al Khobar (13%), Al Qatif (11%), Al Jubail (10%), and Hafar Al Batin (9%). Meanwhile, smaller cities such as Al Khafji, Abqaiq, Al Nairyah, Ras Tanura, Qaryat Al Ulya, and Al Adid together make up less than 5% of the total population. Overall, the Eastern Province has a population of 5,125,254 (Figure 9), which serves as an important baseline for estimating futurewastegeneration.

4.1. Projected MSW Generation and Population Growth

Previous studies indicate that the Eastern Province generates approximately 1.24 kg of MSW PPPD (Radwan et al., 2021). Based on this rate and the official population growth projections, this study estimates future population growth and the corresponding increase in MSW generation across cities in the Eastern Province from 2022 to 2060. The results are presented in Figure 9–12, grouped by city size: major, medium, and small cities. Overall, the results show a clear and steady increase in MSW generation across all cities. This pattern closely follows population growth, reinforcing the strong link between demographic expansion and waste generation. Major cities such as Al Dammam, Al Ahsa, and Al Khobar account for the highest levels of waste generation, which is expected given their larger populations, expanding urban areas, and higher levels of economic activity. Among them, Al Dammam stands out, showing the most noticeable increase over time, reflecting both its population concentration and consistent per capita waste generation (Figure 10). The absolute numbers are presented in Appendix

B.

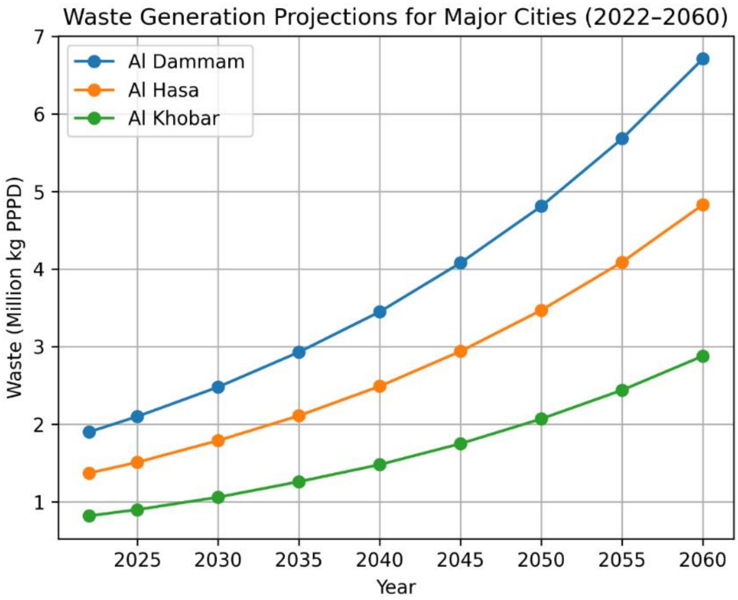


Figure 10. Projected waste generation trends for big cities in the Eastern Province (2022–2060), expressed in million kg PPPD.

Medium-sized cities, including Al Jubail, Al Qatif, and Hafar Al Batin, also show a steady and proportional increase in waste generation. Although their total volumes remain lower than those of major cities, the upward trend is clear and reflects ongoing urban growth and increasing consumption patterns (Figure 11).

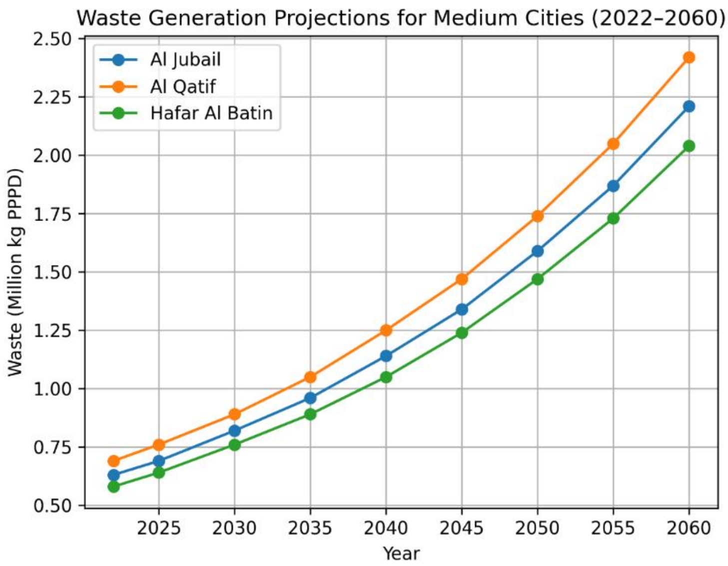


Figure11. Projected waste generation trends for medium-sized cities in the Eastern Province (2022–2060), expressed in million kg PPPD.

A similar pattern can be observed in smaller cities such as Al Khafji, Al Nairyah, Abqaiq, Ras Tanura, Qaryat Al Ulya, and Al Adidwhere waste generation remains relatively low in absolute terms but continues to rise over time. Interestingly, some of these cities display overlapping trends, suggesting similar population sizes and development paths. This indicates that, despite their smaller scale, these cities are experiencing comparable waste generation dynamics (Figure 12).

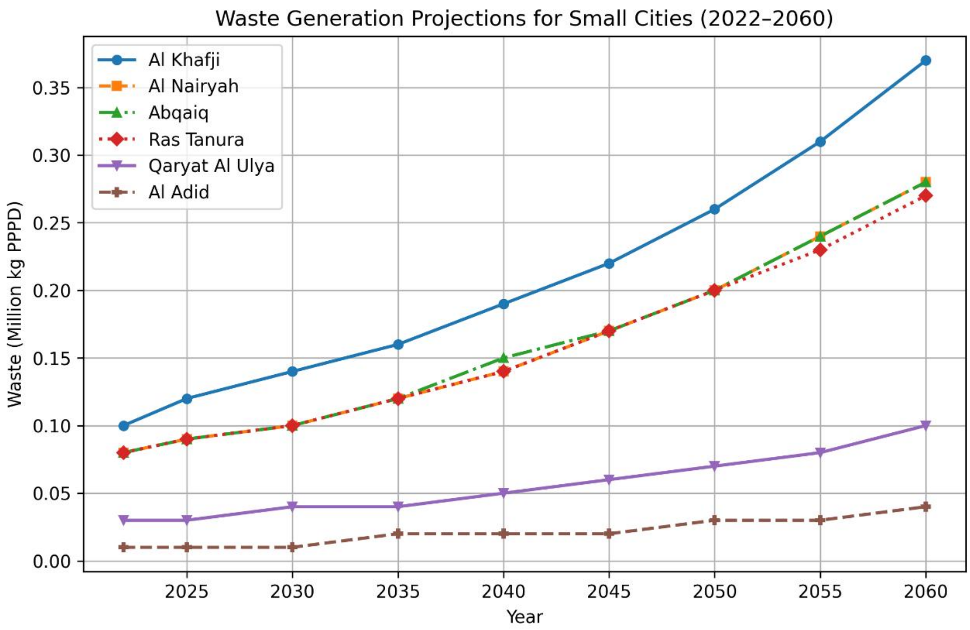


Figure 12. Projected waste generation trends for small cities in the Eastern Province (2022–2060), expressed in million kg PPPD.

At the provincial level, total MSW generation is expected to increase significantly by 2060. Assuming a constant PPPD rate of 1.24 kg, an increase of 1 million residents would result in approximately 1,240 additional tons of waste per day, or more than 450,000 tons annually. This highlights the growing pressure on existing waste management systems and suggests that current approaches may not be sufficient to meet future demand.

4.2. Interpretation of Results

The results clearly show that MSW generation in the Eastern Province is closely linked to rapid population growth and ongoing urbanization. As cities expand and consumption patterns increase, waste volumes rise accordingly, placing growing pressure on infrastructure, environmental systems, and service delivery. This trend is consistent with national projections, which highlight the continued growth of MSW generation in Saudi Arabia driven by urbanization and demographic expansion (Hadidi et al., 2020). From a planning perspective, these trends raise important concerns about the continued reliance on landfill-based disposal. As waste volumes increase, more land, greater operational capacity, and stronger environmental management efforts will be required. Without improvements in current waste management practices, this could lead to higher greenhouse gas emissions, environmental degradation, and increased economic costs. These findings are in line with previous research emphasizing the environmental and social impacts of inadequate MSW management systems (Labib et al., 2023), as well as global evidence linking urban growth to waste management challenges.

4.3. Scenario-Based Interpretations

To better understand possible future pathways, the projected results can be interpreted through three development scenarios. Under a business-as-usual scenario, waste generation is likely to continue increasing steadily, reflecting current trends and an ongoing reliance on landfill-based disposal (Birgen et al., 2024). In contrast, a moderate improvement scenario assumes gradual progress in waste management practices, such as higher recycling rates and greater public awareness, which can help slow down the rate of growth. A more advanced and transformative approach is reflected in the circular economy scenario, where waste segregation, recycling systems, and WtE technologies are widely adopted (Setyono et al., 2025). In this case, waste is no longer seen as a problem to be disposed of, but as a valuable resource that can significantly reduce environmental impacts.

These pathways are supported by recent research highlighting the important role of circular economy strategies and WtE technologies in moving away from traditional linear waste systems toward more sustainable and resource-efficient models. Scenario-based approaches have also been widely used to show how improvements in recycling, sorting, and energy recovery can contribute to long-term sustainability while reducing dependence on landfills (Birgen et al., 2024; Setyono et al., 2025).

4.4. Energy Recovery Potential for MSW

The projected increase in MSW presents a significant opportunity for renewable energy generation. Instead of being treated solely as a disposal issue, MSW can be used as a valuable resource when appropriate technologies are applied. The effectiveness of this process depends largely on the composition of the waste. Organic waste, which makes up a large share of MSW in Saudi Arabia, is well suited for biological treatments such as anaerobic digestion, allowing for the production of biogas as a form of renewable energy. At the same time, recent studies highlight the growing role of thermochemical technologies, particularly pyrolysis, in converting waste into useful renewable energy products such as bio-oil, biochar, and syngas. These approaches support both energy recovery and resource use within a circular economy framework (Ungureanu et al., 2025; Islam, 2024). Materials such as plastics, textiles, and rubber, which have higher calorific values, are more suitable for thermal treatment processes, including pyrolysis and refuse-derived fuel systems. These technologies offer a more sustainable alternative to landfill disposal by generating renewable energy while reducing environmental impacts (Rahman, 2025). Integrating these approaches into existing WM systems can help reduce reliance on landfills while improving resource recovery, reinforcing the role of MSW within a circular economy and supporting Saudi Arabia's renewable energy transition.

Building on the earlier discussion of WtE technologies and MSW energy content, a simplified estimation can be used to better understand the scale of renewable energy potential. Recent studies suggest that MSW typically has an energy content ranging between 8 and 12 MJ/kg, depending on its composition (Ungureanu et al., 2025; Rahman, 2025). Assuming an average value of 10 MJ/kg, one ton of MSW can generate approximately 2.78 MWh of renewable energy. Based on the projected increase of 1,240 tons of waste per day for every additional one million residents, this corresponds to about 3,447 MWh per day, or more than 1.25 TWh annually. This highlights the significant role MSW can play in supporting renewable energy generation and reducing reliance on conventional energy sources when integrated into WtE systems (Islam, 2024).

4.5. Economic Consideration

From an economic perspective, implementing WtE technologies requires significant upfront investment in infrastructure and operational systems. However, these initial costs can be gradually offset through a range of long-term benefits, including electricity generation, heat recovery, and the production of value-added by-products. In addition, reducing reliance on landfills can help lower environmental remediation costs and ease pressure on land use. When supported by appropriate policies and investment strategies, WtE systems have the potential to contribute not only to environmental sustainability but also to long-term economic efficiency.

4.6 Synthesis of Findings

At the provincial scale, total MSW generation is projected to increase steadily through 2060. Assuming a constant generation rate of 1.24 kg per person per day, an increase of 1 million residents would generate approximately 1,240 additional tons of waste daily, equivalent to more than 450,000 tons annually. This highlights the scale of future waste challenges and the urgent need to transition from landfill dependent systems to more sustainable and integrated waste management approaches.

These findings are consistent with earlier national and regional studies. (Hadidi et al. 2020) projected continuous growth in MSW generation in Saudi Arabia driven by population expansion and urbanization, while (Labib et al. 2023) emphasized the associated environmental and social impacts, including increased emissions, land use pressures, and public health risks. The projections in this study reinforce these concerns, particularly as larger urban centers are expected to generate the majority of future waste. International experience further supports these results. Countries such as Japan and Sweden managed similar growth in waste generation through early adoption of WtE technologies, source separation, and circular economy strategies (Hotta and Aoki-Suzuki, 2014; Avfall Sverige, 2022). In contrast, continued reliance on landfilling in Saudi Arabia places the Eastern Province at risk of rising environmental and economic costs.

Overall, population growth remains the primary driver of MSW generation in the Eastern Province. Without effective interventions, including waste reduction, improved recycling, and wider implementation of waste to energy technologies, the region is likely to face increasing pressure on landfill capacity, environmental degradation, and growing economic and social challenges. These findings highlight the importance of integrating MSW management into Saudi Arabia's Vision 2030 through circular economy approaches that treat waste as a resource and support sustainable urban development (Nizami et al., 2017; Abdullah et al., 2022).

5. Conclusion

This study demonstrates that municipal solid waste generation in the Eastern Province of Saudi Arabia is increasing steadily as a result of rapid population growth and ongoing urbanization. Using a projected annual growth rate of 3.375%, the findings show that waste volumes across the province's major cities will continue to rise, placing significant pressure on existing waste management systems. If current landfill-dependent practices persist, environmental and social risks, including greenhouse gas emissions, land degradation, and public health concerns, are likely to intensify. These results are consistent with previous studies and underscore the urgent need to transition toward more sustainable and integrated MSWM approaches.

To address these challenges, policymakers should prioritize the adoption of circular economy–oriented strategies that emphasize waste reduction, reuse, recycling, and WtE technologies in alignment with Saudi Vision 2030. Regulatory reforms, economic instruments such as landfill taxes and incentives for waste segregation, and investments in modern waste management infrastructure are essential to improving system efficiency. Moreover, strengthening public awareness programs and aligning waste management practices with social and cultural values, including Islamic environmental principles, can enhance residents' willingness to participate in waste sorting and recycling initiatives. Evidence from the literature indicates that when adequate infrastructure and incentives are in place, public engagement in sustainable waste practices increases significantly.

Despite its contributions, this study is limited by the absence of a detailed economic and cost–benefit analysis of alternative MSWM scenarios and infrastructure investments in the Eastern Province. Future research should therefore focus on evaluating the financial feasibility and life-cycle impacts of innovative waste management technologies, including WtE systems, as well as conducting comparative analyses of centralized and decentralized waste management models. Such investigations would provide more robust evidence to support policy decisions and help guide the development of resilient, cost-effective, and environmentally sustainable waste management systems in Saudi Arabia. In addition, to build on this study by incorporating spatial analysis tools such as Geographic Information Systems (GIS) to improve waste collection efficiency and optimize facility locations. In addition, behavioral studies focusing on public participation and waste segregation practices would provide valuable insights into improving waste management performance. These approaches would help support more effective and locally adapted waste management strategies in the Eastern Province.

Appendix A: Definition of Terms

Abbreviation	Definition
3Rs	Reduce, Reuse, Recycle
CE	Circular Economy
CO_2	Carbon dioxide
DMA	Dammam Metropolitan Area
EPR	Extended Producer Responsibility
FSI	Fragile States Index
G20	Group of Twenty
GASTAT	General Authority for Statistics
GCC	Gulf Cooperation Council
GHG	Greenhouse Gas
GIS	Geographic Information Systems
Kg	Kilogram
MJ/kg	Megajoules per kilogram
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
MWAN	National Center for Waste Management
NCEC	National Center for Environmental Compliance
PPPD	Per Person Per Day
RDF	Refuse-Derived Fuel
SDGs	Sustainable Development Goals
SIRC	Saudi Investment Recycling Company
SWM	Solid Waste Management
TJ	Terajoules
TWh	Terawatt-hours
UN	United Nations
WM	Waste Management
WtE	Waste-to-Energy

Appendix B: Projected waste generation trends for big cities in the Eastern Province (2022–2060), expressed in million kg PPPD

City	PP 2022	PP 2030	PP 2040	PP 2050	PP 2060	PW 2022	PW 2030	PW 2040	PW 2050	PW 2060
Al Dammam	1.53M	2.00M	2.79M	3.88M	5.41M	1.90M	2.48M	3.45M	4.81M	6.71M
Al Hasa	1.10M	1.44M	2.01M	2.80M	3.90M	1.37M	1.79M	2.49M	3.47M	4.83M
Al Jubail	0.51M	0.66M	0.92M	1.28M	1.78M	0.63M	0.82M	1.14M	1.59M	2.21M
Al Khafji	0.08M	0.11M	0.15M	0.21M	0.30M	0.10M	0.14M	0.19M	0.26M	0.37M
Al Khobar	0.66M	0.86M	1.20M	1.67M	2.32M	0.82M	1.06M	1.48M	2.07M	2.88M
Al Nairyah	0.06M	0.08M	0.12M	0.16M	0.23M	0.08M	0.10M	0.14M	0.20M	0.28M
Al Qatif	0.55M	0.72M	1.00M	1.40M	1.95M	0.69M	0.89M	1.25M	1.74M	2.42M
Al Adid	0.009M	0.011M	0.016M	0.022M	0.030M	0.011M	0.014M	0.019M	0.027M	0.038M
Abqaiq	0.06M	0.08M	0.12M	0.16M	0.23M	0.08M	0.10M	0.15M	0.20M	0.28M
Hafar Al Batin	0.47M	0.61M	0.85M	1.18M	1.65M	0.58M	0.76M	1.05M	1.47M	2.04M
Qaryat Al Ulya	0.02M	0.03M	0.04M	0.06M	0.08M	0.03M	0.04M	0.05M	0.07M	0.10M
Ras Tanura	0.06M	0.08M	0.11M	0.16M	0.22M	0.08M	0.10M	0.14M	0.20M	0.27M

Author Contributions

Conceptualization, J.TA.; methodology, J.TA.; software, J.TA.; U.L.D. and J.T.A.; formal analysis, U.L.D and J.T.A.; investigation, J.T.A.; resources, J.T.A. and U.L.D.; data curation, J.T.A.; writing—original draft preparation, J.T.A.; writing—review and editing, U.L.D. and J.T.A.; visualization, U.L.D.; supervision, U.L.D.; project administration, J.T.A.; funding acquisition, J.T.A. and U.L.D. All authors have read and agreed to the published version of the manuscript. Authorship must be limited to those who have contributed substantially to the work reported.

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Conflict of Interest Statement

The authors declare no conflict of interest.

Ethical Statement

This study does not involve human or animal participants.

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