

Article

An Environmental Assessment of Municipal Solid Waste Management Strategies in Riyadh, Saudi Arabia: A Comparative Life Cycle Analysis

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Abstract: The environmental implications of various municipal solid waste (MSW) management systems in Riyadh, Kingdom of Saudi Arabia, were analysed considering the Riyadh Green Initiative through a comprehensive Life Cycle Assessment (LCA). This study evaluates five distinct scenarios: unsanitary landfilling (Sc0), incineration (Sc1), and a combination of technologies such as anaerobic digestion (AD) and a material recovery facility (MRF) in scenarios Sc2–Sc4. These scenarios were assessed using GaBi 9.2.1 software, employing the impact methodology outlined by CML (2001) to evaluate eight impact categories, including Global Warming and Acidification Potentials, among others. The findings indicate that scenarios incorporating the treatment of 100% of recyclable and organic waste through AD exhibited substantial environmental benefits. Additionally, Sc2 demonstrated the lowest environmental burdens across all impact categories. In contrast, Sc0 ranked the worst in all categories due to the absence of gas and leachate treatment. The results were shown to be reliable when compared qualitatively to previous studies. Furthermore, a sensitivity analysis was conducted to assess this study's system boundaries and the impact of the MRF rate. Overall, this research provides valuable insights for optimising MSW management practices in Riyadh, aiming to reduce their environmental impacts and align with the goals of the Riyadh Green Initiative.

Keywords: municipal solid waste (MSW); life cycle assessment (LCA); environmental impact assessment; waste treatment technologies; Saudi Arabia



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1. Introduction

1.1. Background

Municipal solid waste (MSW) is one of the most pressing global challenges of our time, arising as a direct consequence of diverse human activities in urban areas [1]. MSW significantly contributes to climate change through the emission of greenhouse gases (GHGs) [2], primarily in the form of methane (CH₄), carbon dioxide (CO₂), and nitrous oxide (N₂O) [3]. According to the world bank, in 2016, the management of solid waste produced 1.6 billion t of CO₂ equivalent, accounting for approximately 5% of the world's total GHG emissions [4]. MSW consists of various materials discarded from multi- and single-family residences, institutions, commercial facilities, and industries. It encompasses categories such as organic waste, paper, paperboard, ferrous and non-ferrous metal, glass, plastic, textile, leather, and more [5]. A comprehensive waste management system includes the treatment and disposal of waste, transportation and storage, and labour training [6].

Accurate information on MSW production rates, volumes generated, composition, sources, and the location of waste is essential for effective MSW management, including storage, collection, disposal, and recycling [7]. The aim of an MSW management system is to address environmental, land-use, resource, aesthetic, economic, and health issues related to improper waste disposal [8]. In general, waste management comprises five key elements. The first element involves raising awareness of environmental effects of waste generation;

reusing waste is the next phase, followed by recycling. Additionally, waste-to-energy processes are considered the next step. Disposal in landfills is the final step and is the least favoured waste management approach [5]. A study by Nizami et al. [9] showed that solid waste management expenses are projected to increase from the current annual figure of USD 205.4 billion to approximately USD 375.5 billion by 2025, on a global scale. Furthermore, it is estimated that the global municipal waste recycling industry alone has the potential to generate approximately USD 410 billion, with a quarter of this waste being recycled or recovered for beneficial uses. In certain regions of the world, the high costs of food and animal feed are linked to the production of fuels from feedstocks cultivated on productive agricultural land [9]. According to the world bank [4], global waste generation is projected to reach 3.40 billion t by 2050, with the largest contributions originating from South Asia, East Asia, and the Pacific regions. Conversely, the Middle East and North Africa are forecasted to have the lowest waste volumes across all three time periods: 2016, 2030, and 2050, producing 129 million t, 177 million t, and 255 million t, respectively. Europe and Central Asia are expected to experience a moderate increase of approximately 50 million t over the same period. The symbolic association between food waste and perceptions of abundance has increasingly become a matter of societal concern [10]. Consequently, the predominant type of MSW globally is organic, accounting for more than 60% of waste in East Asia, the Pacific, and the Middle East and North Africa (MENA) [9]. Furthermore, nearly one-third of the global food supply intended for human consumption, equivalent to approximately 1.3 billion t, is discarded annually. In the United States, food waste amounts to 38 million t per year, while in China, it exceeds 90 million t [11]. In Sweden, approximately 33% of the total food consumed is wasted [10]. It is projected that food waste in Asian countries will rise to 4.16 billion t by 2025 [12].

Life Cycle Assessment (LCA) is a method used to evaluate the environmental impact of a product across its entire life cycle, encompassing raw material extraction and processing, production, distribution, use, recycling, and final disposal [13]. In recent years, LCA methodology has been gaining increasing attention [14]. The results of LCA can be utilised to identify opportunities for improvement in manufacturing processes, support strategic planning, and inform public policy [15]. The European Commission recommends that the selection of waste management methods should be based on identifying the most environmentally favourable alternative, as determined by data from LCA [16]. Numerous studies have applied LCA to different types of waste using various scenarios, including diverse waste treatment combinations, to recommend the most effective strategies for sustainable waste management and energy recovery. It has been widely utilised across the globe, particularly in countries such as Australia [17], China [18], the UK [2], Brazil [19], India [20,21], and Saudi Arabia [22–24].

Wang et al. [2] conducted a study using LCA to examine the Global Warming Potential (GWP) of MSW management in Nottingham, UK. The findings demonstrate that improvements in waste collection, treatment, recycling systems, and efforts to reduce waste have gradually decreased GHG emissions from MSW management. The study further highlights that food waste sorting and AD treatment contribute to a greater reduction in environmental impact. In a study by Dastjerdi et al. [17], five MSW management options in New South Wales, Australia, were assessed, including both energy and material recovery. The scenario that generated the most electricity consistently utilised AD for food waste, incineration for plastics and other combustibles, and landfilling for non-combustible materials. The scenario with the lowest GWP involved recycling plastics, incinerating or gasifying combustible materials, using AD for food waste, and landfilling non-combustibles. Zhou et al. [18] examined Hangzhou's MSW management system from 2007 to 2016 using LCA analysis. Their findings indicate that the environmental impacts of incineration, such as GWP and AP, are lower compared to landfilling. Additionally, the study suggested that AD could be a viable solution for managing food waste. Another study in the Greater London area compared two approaches to managing plastic solid waste using LCA. The results show that incineration, particularly when combined with heat and power (CHP) generation and

a dry MRF, has a lower environmental impact compared to landfilling [1]. In Brasilia, Brazil, a study was conducted on MSW management through LCA analysis [19]; while the city currently relies on landfilling, the report proposed four refuse-derived fuel (RDF)-based solutions. These solutions demonstrated a reduction in emissions by 2% to 23%, outperforming previous waste management methods. Moreover, it has the potential to significantly reduce the environmental impacts of current waste disposal methods. The research also demonstrated that replacing coke with RDF in cement kilns offers environmental benefits.

An LCA of MSW management in Nagpur, India, highlighted the importance of recycling in minimising environmental impacts. The study concluded that the optimal approach is a combination of recycling, composting of biodegradable waste, and landfilling residuals [20]. Another LCA study of MSW in Delhi found that landfilling and transportation pollutants pose significant environmental risks. The study highlights the crucial role of recycling in promoting environmental sustainability [21]. In Riyadh, Saudi Arabia, an LCA was conducted to compare various MSW management alternatives, including MRFs, AD, and waste to energy (WTE) [25]. This evaluation aligns with Riyadh's 2045 Strategy, initiated in 2016. The findings emphasise that recycling and waste-to-energy treatments are essential for improving MSW management and reducing GHG emissions. Additionally, these methods support green energy production and material recovery, key principles of the circular economy [25]. An LCA of MSW in Madinah, Saudi Arabia, evaluated outputs such as CO₂, products, and energy [22]. The results indicate that prioritising recycling, followed by composting, leads to the lowest CO₂ emissions and the highest good production [22]. In Al-Hasa, Saudi Arabia, research applied LCA and life cycle cost methodologies to assess the environmental and economic impacts of MSW on air, soil, groundwater, and noise quality [24]. The study found elevated anion levels in soil and groundwater due to the absence of a landfill liner and leachate leakage [24]. Another study by Almadhi et al. [23] focused on the LCA of plastic waste only in Saudi Arabia, revealing that a combination of mechanical recycling and pyrolysis has the least environmental impact. This approach accommodates a broader range of plastic waste and improves waste management, supporting a circular economy. However, the study's reliance on data from the Eco-invent 3.9.1 database and peer-reviewed studies may limit its applicability to the specific conditions in the Kingdom. Additionally, the mechanical separation and recycling of plastic waste, particularly food packaging waste, present significant challenges, even with the use of the infrared automated separators [26].

Previous studies have shown that landfills significantly contribute to GWP and exacerbate environmental harm, especially compared to less damaging technologies. This paper focuses on assessing the environmental impact of MSW management systems using LCA, in alignment with the Green Saudi Arabia Initiative, through a case study in Riyadh. This study aims to evaluate and compare the environmental benefits of energy recovery within the existing MSW management system, in the context of the Saudi and Riyadh Green Initiatives.

1.2. Case Study

The Kingdom of Saudi Arabia (KSA), located in the Middle East between 16°22' and 32°14' North and 34°29' and 55°40' East [27], covers an area of 2,150,000 km², making it one of the largest countries in the region. Riyadh, the capital, is the largest city. The KSA has a population density of approximately 15.61 people per square kilometre and an annual growth rate of 3.4%; the current population is over 32.175 million [8,22,28]. The KSA's waste management system is basic, largely relying on outdated landfills for MSW disposal. Challenges include a growing population, cultural differences, and limited awareness of solid waste's environmental impacts [7]. Additionally, MSW in the KSA generates about 28.1 million t of CO₂ equivalent per year in GHGs [29].

2. Materials and Methods

Riyadh, the capital and largest city of Saudi Arabia, is located on the eastern Najd Plateau within the an-Nafud desert [30]. With a population of just over 7 million, Riyadh is the most populous city in the country [31], and its population is expected to reach at least 15 million by 2030 [32]. Of the four landfills in Riyadh, three have been closed, leaving only the Al-Sulay Landfill, which spans 8 million square metres and is located about 25 km from the city centre. Each day, over 16,000 t of waste are transported to this landfill [33,34].

2.1. Waste Composition

The global average for MSW is 1.2 kg per person per day. In Saudi Arabia, however, the rate exceeds this norm, averaging at 1.4 kg per person per day [34]. With a national population of 32.175 million and 7 million residing in Riyadh [31], the total MSW amounts to 16.44 million t per year nationwide and 3.5 million t per year in Riyadh. The waste composition is shown in Figure 1.

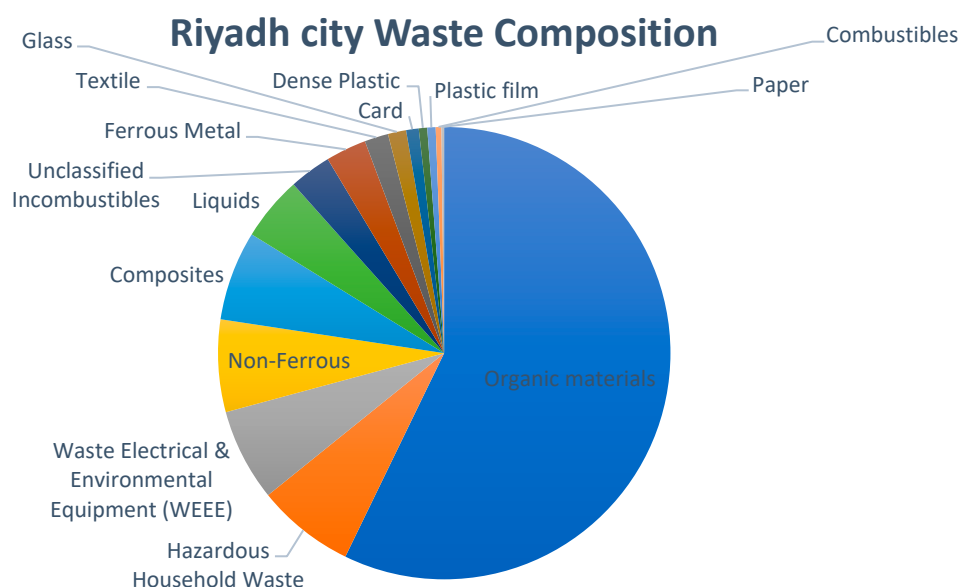


Figure 1. Riyadh city waste composition in 2015 [34].

2.2. Life Cycle Assessment (LCA)

The LCA methodology was employed in this study to assess the environmental impacts of various MSW management technologies. The framework follows ISO 14040 standards [35,36], which outline four phases of LCA: defining the goal and scope, conducting life cycle inventory analysis, performing life cycle impact assessment, and interpreting the data [35]. According to the U.S. Environmental Protection Agency (EPA), the LCA process also includes four stages: raw material extraction, production, product consumption, and disposal [37].

2.2.1. Goal and Scope

The aim of this study is to assess the environmental impacts of various MSW scenarios using GaBi 9.2.1 software, guided by the Saudi and Riyadh Green Initiatives, which aim to transform MSW management in Riyadh by 2035. The primary focus is on MSW management in Riyadh, with a functional unit of 1 t of MSW generated. The system boundaries, shown in Figure 2, include waste disposal by households, collection, transportation, and final delivery to landfills, incineration facilities, AD plants, and MRFs.

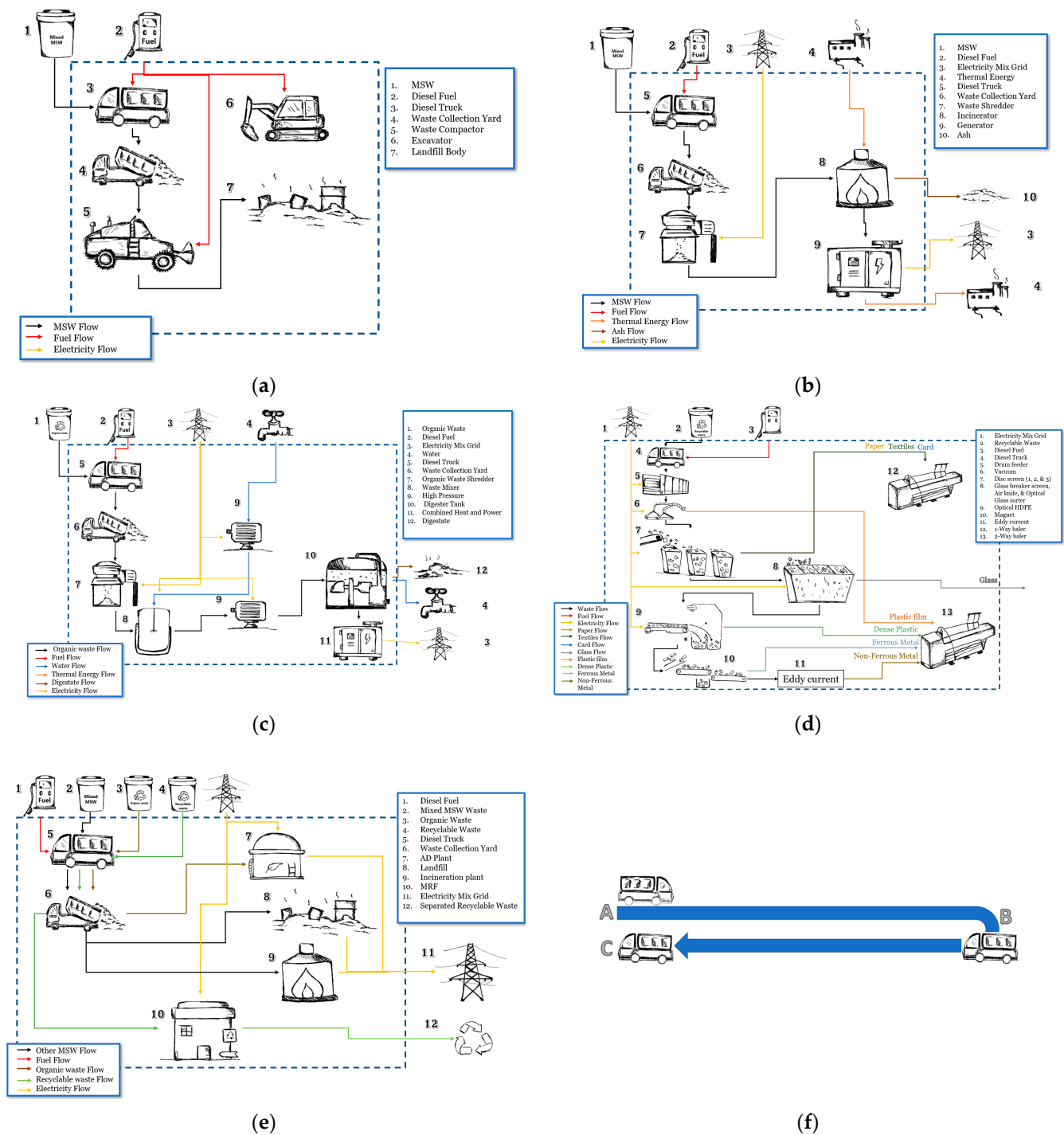


Figure 2. (a) Baseline scenario (Sc0) system boundaries, (b) first scenario (Sc1) system boundaries, (c) first sub-scenario (Sub-Sc.a) system boundaries, (d) second sub-scenario (Sub-Sc.b) system boundaries, (e) second scenario (Sc2) system boundaries, (f) transportation plan.

2.2.2. Scenarios Description

The Saudi and Riyadh Green Initiatives aim to transform MSW management in Riyadh by developing a sustainable waste management approach that can be implemented across the Kingdom. The goal is to divert 94% of Riyadh's waste from landfills and compost over 1.3 million t of biodegradable waste by 2035, reducing CO₂ emissions by 4.1 million metric t per year [38]. Four alternative waste management scenarios, along with two sub-

scenarios, have been formulated for MSW disposal based on the 2035 strategy, as shown in Table 1 [38].

Table 1. Scenario description.

Waste Treatment	Sc0	Sc1	Sc2	Sc3	Sc4
Unsanitary Landfill	100%	0%	0%	0%	0%
Sanitary Landfill	0%	0%	6%	6%	0%
Incineration	0%	100%	24.9%	4%	10%
AD	0%	0%	36.30%	57.20%	57.20%
			(Only organic waste)	(Only organic waste)	(Only organic waste)
MRF	0%	0%	32.8%	32.8%	32.8%
			(Only recyclable waste)	(Only recyclable waste)	(Only recyclable waste)

Figure 2a illustrates the current waste management system, known as the baseline scenario (Sc0). Figure 2b–e present various options for residual waste management in the study area. To support the green Riyadh strategy, two sub-scenarios were developed: Sub-Sc.a involves treating organic waste through AD and Sub-Sc.b focuses on processing recyclable waste via an MRF, as shown in Figure 2b,c. Additional scenarios were created to evaluate the power generation capacity and environmental impacts, with comparisons made to the baseline Sc0 scenario.

Sc0, the baseline scenario depicted in Figure 2a, assumes that all MSW is collected by trucks and disposed of in an open unsanitary landfill without gas or leachate treatment, reflecting the current practice in Riyadh. The Al-Sulay Landfill, located approximately 25 km south-east of the city centre, spans 8 million square metres and exclusively accepts MSW, strictly prohibiting medical, industrial, and hazardous waste. The facility handles around 2000 trucks daily, transporting over 16,000 t of MSW [33,34,39]. According to Osra et al. [40], methane (CH₄) landfill emissions are 83.52 m³ per t. In alternative scenarios, a sanitary landfill with leachate treatment and gas capture, as found in the GaBi database, is assumed.

Sc1, depicted in Figure 2b, assumes that all MSW will be sent to an incineration plant for management. It is a standard practice to mix the waste feedstock before incineration to ensure a consistent heating value. The feedstock is then transferred to a large hopper, bunker, or similar system for burning [8]. The outputs of incineration include hot combustion gases, primarily composed of CO₂, nitrogen (N₂), oxygen (O₂) and flue gas [41]. The GaBi database models an incineration plant used in this scenario, which produces both electricity and steam. The plant operates with an average engine efficiency of around 82%, utilising the generated steam internally for process use, with the remaining steam used to generate electricity for households. The facility employs dry flue gas cleaning and Selective Non-Catalytic Reduction (SNCR) to remove NO_x. Bottom ash, which amounts to approximately 220–250 kg per t of MSW, is quenched, and ferrous scrap along with some non-ferrous metals (aluminium, copper, brass, zinc, and lead) are extracted and recovered. According to the GaBi database, after metal recovery, bottom ash is repurposed for construction materials, and a three-month ageing process is conducted to stabilise it [42]. This process may convert the bottom ash into a more stable and less hazardous substance, making it suitable for various applications, including construction materials [43], as assumed in both the GaBi database documentation and this study [42]. When bottom ash is used as a component in concrete, the cement functions to contain heavy metals, both chemically and physically [44].

Furthermore, based on a review, bottom ash may substitute up to 80% of natural fine aggregates, specifically replacing fine particles, not coarse ones. It may also enhance the resilient modulus, tensile strength, and fracture behaviour of asphalt mixtures by up to 60% when used as a filler. Consequently, bottom ash may serve as a partial substitute for fine aggregates in hot mix asphalt applications, contingent upon the chemical structure

of the ashes and after suitable treatments, with anticipated sufficient performance and technical attributes for asphalt road applications. A key rationale for using bottom ashes in cement clinker manufacture is their chemical structure, which closely resembles that of the raw materials used for cement clinker. Numerous methods exist for using bottom ashes in the manufacturing of cement clinker. One of the methods entails substituting the cement clinker's source material with bottom ash. In terms of the porosity in concrete, reports indicate that metallic components, especially metallic aluminium, in ash may produce hydrogen gas in concrete. The gas produced inside the concrete might lead to volumetric expansion, which will increase its porosity. Consequently, specialists have suggested prewashing bottom ash with either acidic or alkaline water. The prewashing technique may stabilise or remove metallic components in the ash prior to its incorporation into the concrete matrix [44]. The contaminants from bottom slag are mitigated using a three-month ageing process that decreases their pollutants (solubility and leaching potential) [42,43].

Sub-Sc.a, illustrated in Figure 2c, involves AD, a widely recognised method for converting organic waste into energy [45]. According to Ouda et al. [41], AD is the preferred treatment for organic waste compared to pyrolysis, gasification, incineration, and RDF. Additionally, one of the goals of the Riyadh Green Initiative is to treat 1.3 million t of organic waste through composting [38]. In Sub-Sc.a, it is assumed that organic waste is separated at the source, typically from bins in front of households, stores, etc. No machinery is used for separation before the loading phase. The AD facility processes only organic waste, utilising microorganisms to decompose the material in the absence of air or oxygen [5]. The efficiency of this process is estimated at approximately 36% [46]. The primary output of AD technology is biogas [47], which will be used for electricity and production and integrated into the grid to help mitigate environmental impacts. Biogas typically consists of 45–65% CH₄ and 30–40% CO₂. Another byproduct, known as digestate, can be used as a valuable soil fertiliser, potentially providing an additional revenue stream for AD facilities [48].

Sub-Sc.b, depicted in Figure 2d, describes the MRF and recycling process. In this scenario, all recyclable waste is separated at the source using designated bins and is directly delivered to the MRF. Since sorting machinery data was unavailable in the GaBi database, inventory data from Pressley et al. [49] was used to model the process. It is assumed that the MRF employs a single-stream method with an electricity consumption of 6.2 kWh per t and 0.7 L of diesel per t of recyclable waste. Additionally, since the recycling process data was not available in GaBi, the final products from recycling are assumed to result in avoided environmental impacts. Therefore, assumptions for the final products in Sub-Sc.b are presented in Table 2, based on assumptions from previous studies.

Table 2. Final products from recycling.

Category	Final Product (Found on GaBi Database)	As Assumed by
Plastic Film waste	Polyethylene High Density Granulate (HDPE)	[50]
Card waste	Containerboard	[25]
Paper waste	Containerboard	[25]
Textile waste	Cotton textiles	[51]
Dense Plastic waste	Polyethylene High Density Granulate (HDPE)	[50]
Glass waste	Glass containers	[52]
Ferrous metals	Copper, aluminium, and steel	[53]
Non-ferrous metals	Copper, aluminium, and steel	[53]

Sc2: In the second scenario, multiple waste treatments are combined to meet the Riyadh Green goals, as shown in Figure 2. It is assumed that 36.3% of organic waste will be processed through AD, 32.8% of recyclable materials (such as textiles, plastic, paper, glass, and non-ferrous metals) will be sent to the MRF for recycling, 24.9% of MSW will be

incinerated, and only 6% will be sent to landfill. Waste collection is considered beyond the system boundaries, as assumed by other studies [20,25,54,55].

2.2.3. Transportation of the Waste

Considering transportation planning assumptions is essential for a thorough assessment of environmental impacts. In this study, the assumed transportation distance is 25 km, representing the distance between Riyadh's city centre and the landfill, using diesel trucks [33]. It is assumed that trucks are empty on the trip from the landfill to the city centre and fully loaded on the return trip. Transportation estimates are based on a diesel Euro 5 truck with a gross weight of 34–40 t, and a payload capacity of 32 t, as derived from the GaBi database. A truck utilisation factor of 0.45 was applied to simulate the transportation plan.

2.2.4. Life Cycle Inventory (LCI)

During the preparatory phase of the inventory evaluation, a wide range of materials were collected from various sources, including educational institutions, periodicals, government organisations, and the GaBi 9.2.1 database. The data collected included waste quantities and categories, emissions, facilities, energy recovery, and other relevant factors. Careful selection of this data was crucial for an accurate inventory analysis. However, due to limitations in the GaBi 9.2.1 database, some inputs were unavailable. As a result, alternative waste data from the GaBi database were used such as liquids, composites, unclassified incombustibles, combustibles, waste electrical and electronic equipment (WEEE), and hazardous household waste.

3. Results

3.1. Environmental Impact

The results of the LCA can be used to identify opportunities for improving manufacturing processes, assist in setting long-term goals, and inform public policy [15]. Environmental impacts were analysed and classified into various categories across the study scenarios, with results generated using GaBi software (9.2.1.68), a widely utilised LCA tool [42]. The CML 2001 Life Cycle Impact Assessment (LCIA) method was employed to quantitatively evaluate potential environmental impacts [56], including GHG emissions and effects on human health. Classifying these impacts helps provide a comprehensive understanding of environmental effects in different scenarios. The following section compares the environmental impacts of the five selected scenarios based on Green Riyadh's MSW management goals across eight impact categories: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone layer Depletion Potential (ODP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Human Toxicity Potential (HTP), Photochemical Ozone Creation Potential (POCP), and Terrestrial Ecotoxicity Potential (TETP). Figure 3 presents the results for all scenarios.

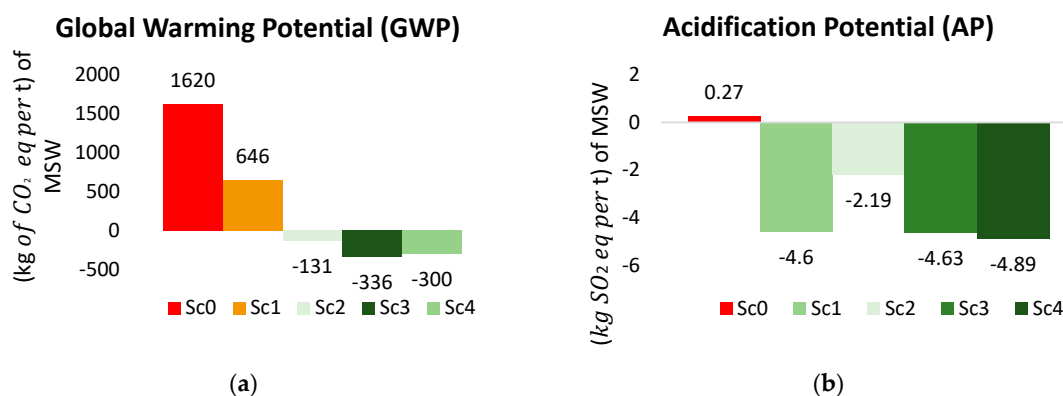


Figure 3. Cont.

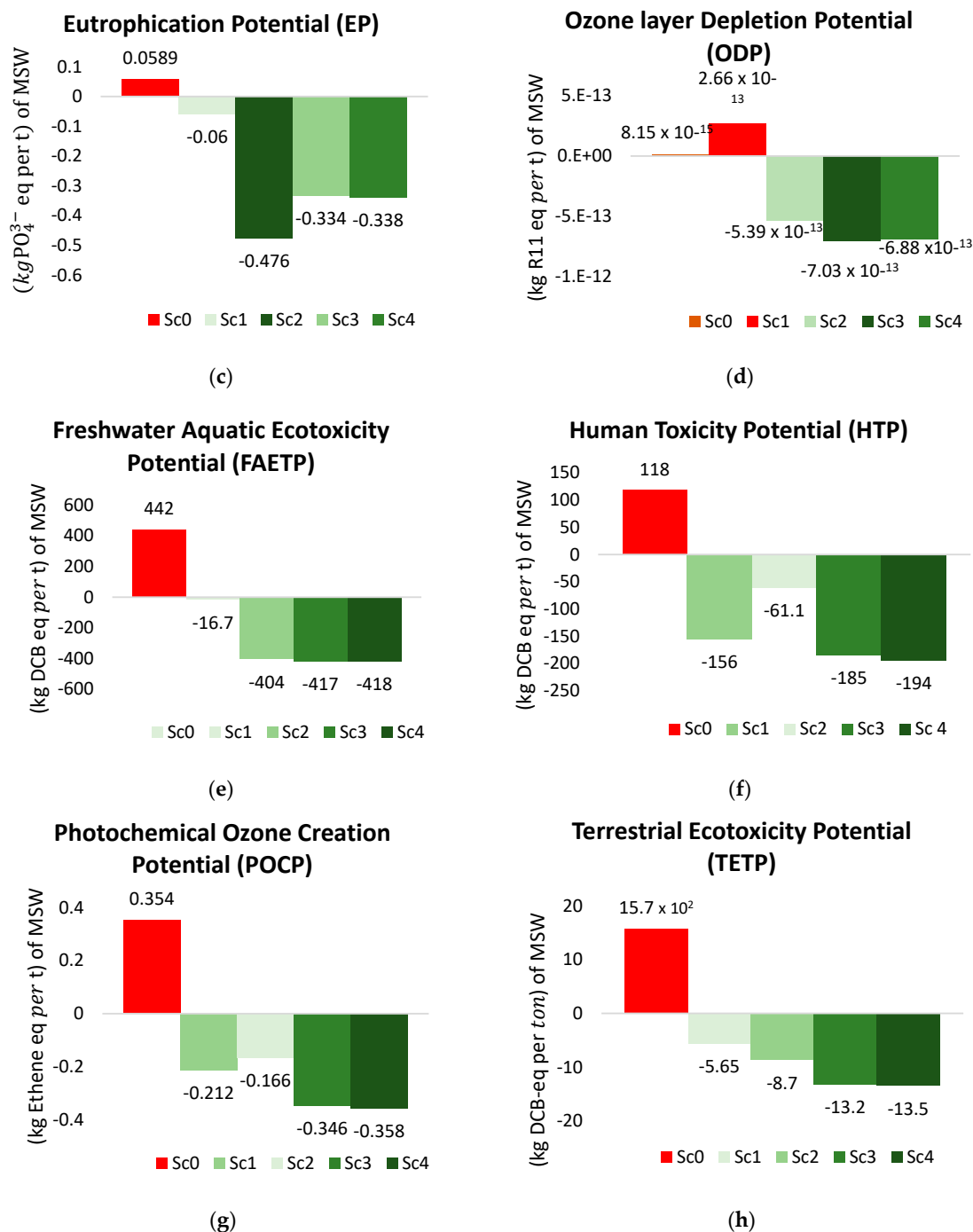


Figure 3. Results for eight impact categories per functional unit (FU). (a) Global Warming Potential; (b) Acidification Potential; (c) Eutrophication Potential; (d) Ozone layer Depletion Potential; (e) Freshwater Aquatic Ecotoxicity Potential; (f) Human Toxicity Potential; (g) Photochemical Ozone Creation Potential; (h) Terrestrial Ecotoxicity Potential.

The highest GWP was observed in the unsanitary landfill, at 1620 kg of CO₂ equivalent per t, primarily due to the absence of gas or leachate treatment. In contrast, incineration with energy recovery (Sc1) significantly reduced GWP to 974 kg of CO₂ equivalent. GWP is driven by the release of GHGs such as CH₄, CO₂, and N₂O, which contribute to rising global temperatures. MSW management typically produces a mix of biogenic and fossil CO₂. Biogenic CO₂ is generated from the decomposition of the biodegradable MSW, while

fossil CO₂ is produced by burning non-biodegradable materials like plastic, textiles, and leather [20].

The negative GWP outcomes in Sc2, Sc3, and Sc4 reflect avoided environmental impact due to the plant's connection to the power grid. Notably, the Green Riyadh goals (Sc2) aim to reduce GWP, with significant reductions achieved by diverting organic waste from landfills and incineration plants to AD. Sc4 proved to be the most environmentally friendly scenario, achieving 100% recycling and organic treatment while eliminating landfilling. This paper calculates GWP over a 100-year timeframe, with the GWP impact category extensively examined in previous studies [2,19,57]. For AP, the highest result for MSW in Sc0 in Riyadh was 0.27 kg SO₂ equivalent per t, while the lowest AP was observed in the 100% organic waste treatment and recycling scenarios (Sc3 and Sc4).

Negative AP values suggest a potential beneficial outcome, but in LCA studies, negative AP does not always indicate an environmental advantage, as acidifying emissions may be absorbed or neutralised within the system boundaries. Conversely, positive AP values suggest the potential for environmental harm, such as contributing to acid rain, following similar trends observed in previous studies [20,21].

The Green Riyadh goal was found to be the most environmentally favourable scenario for EP, with a value of $-0.476 \text{ kg PO}_4^{3-} \text{ eq per t}$. In contrast, the highest EP value for MSW in an open landfill was $0.0589 \text{ kg PO}_4^{3-} \text{ eq per t}$, indicating the potential for nutrient leakage from landfills and its harmful effects on water and soil quality [23,58]. The findings indicate that exclusive use of incineration, as in Sc1, has a detrimental environmental impact, particularly concerning the potential damage to the ozone layer. This is reflected in the ODP, with a result of $2.66 \times 10^{-13} \text{ R11 eq per t}$, primarily due to emissions generated from the incineration of the MSW. In contrast, the value for Sc0 is a very low positive figure, indicating that it does not significantly contribute to ozone depletion. Sc3 showed the lowest ODP with a value of $-7.03 \times 10^{-13} \text{ R11 eq per t}$, following similar trends observed in previous studies [23,25,58,59].

Another important category to consider in waste management is FAETP, which has been examined in several studies [23,25,59,60]. Due to the lack of leachate treatment, Sc0 yielded the highest FAETP value, with 442 kg DCB equivalent per FU. Sc1 showed a reduced FAETP compared to landfilling, indicating a potential decrease in environmental risk. The integration of AD and an MRF with recycling in Sc2, Sc3, and Sc4 resulted in negative FAETP values, suggesting a lower risk of harm to freshwater. The most favourable outcome was achieved in Sc4, with 100% organic waste treated via AD, 100% recyclable waste processed by an MRF and recycling, and zero landfilling, leading to a reduction of $-418 \text{ kg DCB equivalent per FU}$.

Sc1, which involves only incineration, significantly reduced HTP, compared to landfilling. This suggests a lower risk to human health from chemical exposure during incineration compared to potential pollution from landfill leachate. Sc0 had the highest HTP impact, at 118 kg DCB eq per FU. In contrast, Sc2, Sc3, and Sc4, with 100% organic and recyclable waste treatment in Sc3 and Sc4, resulted in negative HTP values, indicating the lowest impact. The HTP category has also been examined in several previous studies [20,23,25,58–61]. The highest positive value for POCP, 0.354 kg Ethene per FU, was observed in landfilling. Conversely, combined waste management treatments like incineration, AD for organic waste, and an MRF for recyclable waste utilised in Sc2, Sc3, and Sc4 showed positive on POCP. While the POCP category has hitherto been studied extensively [20,21,23,58,60,61], findings indicate minimal impact on TETP across all scenarios, except for the baseline, which recorded 1570 kg DCB eq per FU. That suggests potential harm to land-based environments, such as forests and deserts, where ecotoxicity reflects a chemical's capacity to harm organisms. Shifting organic waste from landfills, as in Sc2, Sc3, and Sc4, likely reduces the threat to terrestrial animals, plants, and soil. The TETP category has also been applied in numerous studies, demonstrating similar trends to those observed in this study [23,25,59,60].

3.2. Sensitivity Analysis

Sensitivity analysis examines how outcomes change when specific input parameters are altered, helping to assess the impact of different process parameters on overall performance [21]. In this study, sensitivity analysis was conducted to identify key parameters and evaluate their variations. For the mixed treatment system, the primary factor was the percentage of recyclable waste. In Sc3, 100% of recyclable waste was assumed to be processed by the MRF, while all organic waste was directed to AD. In Scenarios 3.1, 3.2, and 3.3, different percentages of recyclable waste were assumed to be processed by the MRF: 50%, 25%, and 0%, respectively, as shown in Figure 4.

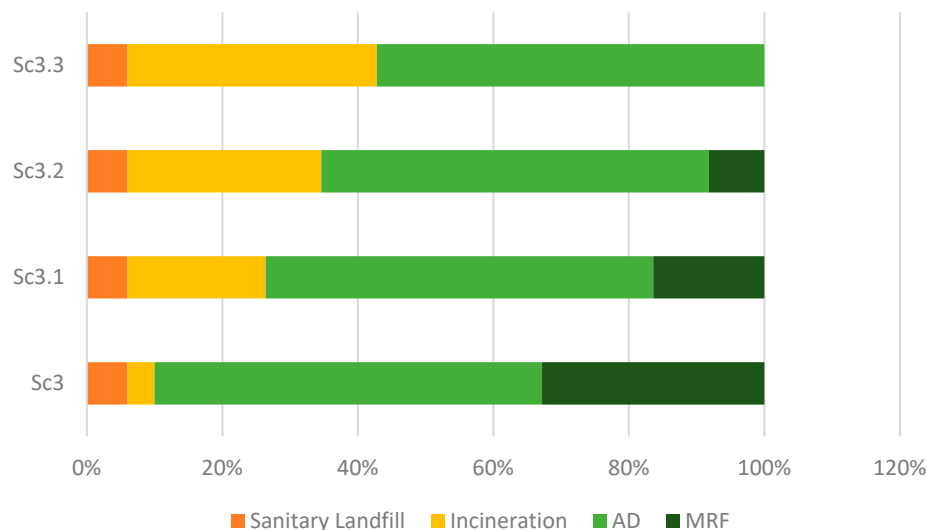


Figure 4. Sensitivity analysis scenarios.

The difference in GWP impact between Sc3 and Sc3.3 was approximately 345 kg CO₂ equivalent per t of MSW. It is evident that increasing the rate of recycling, rather than relying on landfilling or incinerating, offers significant environmental benefits in terms of reducing GHGs. Conversely, incinerating most MSW, excluding organic waste, as in Sc3.3, is more harmful to the environment in five out of eight impact categories compared to recycling. The findings in Table 3 are considered reliable, as no significant variations were observed after conducting the sensitivity analysis.

Table 3. Results per FU for sensitivity analysis.

Impact Category	Unit	Sc3	Sc3.1	Sc3.2	Sc3.3
Global Warming Potential (GWP)	[kg CO ₂ eq.]	−131	−58.8	62.7	214
Acidification Potential (AP)	[kg SO ₂ eq.]	−2.19	−4.58	−4.77	−5.26
Eutrophication Potential (EP)	[kg Phosphate eq.]	−0.476	0.109	0.143	0.161
Ozone layer Depletion Potential (ODP)	[kg R11 eq.]	-5.39×10^{-13}	-5.38×10^{-13}	-2.96×10^{-13}	-1.71×10^{-14}
Freshwater Aquatic Ecotoxicity Pot. (FAETP)	[kg DCB eq.]	−404	−54.5	−33.3	−24.2
Human Toxicity Potential (HTP)	[kg DCB eq.]	−61.1	−206	−215	−231
Photochemical Ozone Creation Potential (POCP)	[kg Ethene eq.]	−0.166	−0.313	−0.31	−0.315
Terrestrial Ecotoxicity Potential (TETP)	[kg DCB eq.]	−8.7	−7.95	−7.89	−8.3

3.3. Comparative Analysis of Findings with Previous Research

Numerous LCA studies have been published on handling MSW via landfill, incineration, and AD, among other methods. However, making direct quantitative comparisons

across these studies is difficult due to variations in system boundaries, assumptions, and methodologies [58]. Table 4 provides an overview of GWP results from LCA studies on MSW worldwide, highlighting the range of findings. All studies use a functional unit of 1 t of MSW. The results of this study will be compared to these findings for context. The GWP result for Sc0 falls within the range reported in six global studies, from 374 kg to 1840 kg of CO₂ equivalent per t of waste. Similarly, the GWP result for Sc1 aligns with seven studies, showing 646 kg of CO₂ equivalent per t. Sc1 was able to reduce GHG emissions by 60.12% compared to Sc0. Scenarios 2, 3, and 4, which use recycling and non-thermal technologies for treating recyclable and organic waste in Riyadh, demonstrate the lowest environmental impacts across most of the eight impact categories. Given these findings, the current MSW management system in Riyadh is considered environmentally unsuitable for future use.

Table 4. Summary of previous LCA studies.

Type	Location (City, Country)	Results (kg CO ₂ eq per FU)	Ref.
Landfill	Sakarya (Turkey)	1840.00	[54]
	New South Wales (Australia)	1370.00	[17]
	Nottingham (UK)	1076.00	[2]
	Sweden	746.45	[61]
	Hangzhou (China)	502.00	[18]
	Yogyakarta (India)	374.00	[62]
	Ranges from 374 to 1840 (kg CO ₂ eq) per FU		
Incineration	Sapporo, Tokyo, Nagoya, Osaka, Kobe, Takamatsu, and Fukuoka (Japan)	716.00	[63]
	Moscow (Russia)	500.00	[57]
	Nottingham (UK)	487.90	[2]
	Sweden	424.40	[61]
	Sapporo, Tokyo, Nagoya, Osaka, Kobe, Takamatsu, and Fukuoka (Japan)	391.00	[63]
	Yogyakarta (India)	346.00	[62]
	Hangzhou (China)	271.00	[18]
	Ranges from 271 to 716 (kg CO ₂ eq) per FU		

4. Discussion

This study examined the environmental impacts of various MSW management options in Riyadh, aligned with the KSA and Riyadh Green Initiatives, using an LCA methodology. Five scenarios were assessed: the baseline scenario of landfill (Sc0), incineration (Sc1), the Green Riyadh Initiative (Sc2), 100% AD for organic waste and 100% recycling for reusable materials with 4% and 6% for landfill and incineration (Sc3), and a combination of technologies including incineration, AD, and an MRF (Sc4). The findings offer insights into the potential environmental impacts of each scenario. Regarding GWP, Sc2, Sc3, and Sc4 showed the most favourable results, with substantial reductions compared to Sc0 for managing all types of MSW. This indicates that adopting these advanced waste management technologies, as opposed to traditional landfilling, could significantly mitigate climate change impacts. Notably, Sc2–4 resulted in negative GWP values, suggesting potential carbon separation, likely due to the connection to the electricity grid and the capture of methane (CH₄) emissions.

When comparing AP across scenarios, open unsanitary landfills had the worst impact. The Green Riyadh Initiative showed favourable AP results, with Sc3 and Sc4 delivering the best outcomes. This suggests that using AD for organic waste and recycling for recyclable materials can effectively reduce the AP. In terms of EP, ODP, and FAETP, scenarios incorporating AD and recycling demonstrated greater environmental benefits compared to Sc0 and Sc1. The ODP results for Sc2, Sc3, and Sc4, which rely on multiple waste management methods, showed lower or negative values, indicating a potential reduction in ozone layer depletion and ozone generation compared to Sc0 and Sc1. It was also found

that there were significant differences in TETP results between the open landfill and other scenarios, with the unsanitary landfill showing the worst impact. It poses a potential threat to land-based environments such as forests, deserts, and other non-aquatic settings, as ecotoxicity potential reflects a chemical's capacity to harm living organisms. The open unsanitary landfill scenario had the most significant negative environmental impact across all variables, including GWP, AP, EP, and POCP. Landfill leachate and methane emissions remain major environmental threats. Sc1 showed notable improvements over current practices, with a 60.12% reduction in GWP compared to Sc0, along with lower FAETP and a significant decrease in POCP, indicating a reduced contribution to ground-level ozone formation.

Sc4 appears to be the most environmentally friendly and sustainable strategy, achieving the best outcomes by eliminating landfilling in five of the eight impact categories. Sc3, which allocates 6% of MSW to sanitary landfill, 4% to incineration, and directs all organic waste to AD and all recyclables to recycling, showed the most significant reductions in GWP and ODP, indicating minimal impact on global warming, human health, and ozone depletion. Meanwhile, Sc2 ranked as the most beneficial in terms of EP.

The findings align qualitatively with previous research. The GWP values for the current MSW management system in Sc0 and Sc1, at 1620 kg and 646 kg of CO₂ equivalent, respectively, are consistent with earlier studies [2,18,57,59,64–67]. Similar to Liikanen et al.'s [68] research, the greatest reductions in AP were observed when AD was used, and grid energy was substituted. As seen in Zhou et al. [18], all energy recovery-based waste management scenarios had negative AP values, indicating environmental benefits. The findings support a shift away from landfilling towards a combination of waste management strategies, such as AD and recycling, as outlined in the Riyadh Initiative [38]. The mixed approach, seen in Scenarios 2–4, offers significant environmental benefits by promoting energy recovery while reducing acidifying emissions and GHG emissions. Similar results have been observed in studies conducted in India, Australia, and England [2,20,59]. However, it is important to note that incineration can still have environmental impacts, such as air pollution. Nevertheless, compared to landfilling, incineration with energy recovery releases fewer GHGs, particularly CH₄ [68].

5. Future Work

The findings of LCA studies can significantly inform future waste management plans, aiding in the design and optimisation of MSW management systems. Based on these results, future research should explore the economic impacts and consider other waste-to-energy technologies. As Riyadh rapidly develops into a smart city with numerous mega projects, an increase in e-waste and construction waste is anticipated, presenting an opportunity for further research into effective management options. Furthermore, incineration plant dioxin, partially solved problems, the presence of heavy metals, and the recycling of ashes as a cement substitute are challenges that need to be addressed in the future.

6. Conclusions

This research highlights the environmental impacts of various MSW management approaches in Riyadh, Saudi Arabia, aligned with the Green Riyadh Initiative's goal for waste management transformation by 2035, using LCA. This study assesses five scenarios: the baseline scenario, involving unsanitary landfilling (Sc0), incineration (Sc1), and a combination of waste management techniques such as sanitary landfilling, WTE technologies, and recycling (Sc2, Sc3, and Sc4). In Sc4, landfilling is prohibited. To study eight estimated environmental impact categories, including GWP, AP, and EP, the LCIA method was employed. The Riyadh Green Initiative scenario (Sc2) showed the lowest negative environmental impacts across all categories compared to Sc0. Sc1 demonstrated a significant 60.12% reduction in GWP compared to Sc0. Sc4 exhibited superior sustainability, outperforming other models in five out of eight impact categories. Additionally, scenarios that treat 100% of organic waste through AD and 100% of recyclable waste via an MRF

and recycling offer substantial environmental benefits compared to open landfilling and incineration methods. The results highlight the importance of replacing the current MSW management system, which relies on open landfills, with more sustainable strategies to reduce environmental impacts. When selecting the appropriate MSW treatment, factors such as the type and quantity of waste should be considered. Despite some limitations in data availability, this study presents several promising ideas for future research, such as focusing on specific types of MSW, like electronic or medical waste, and examining the economic impacts of various waste management approaches.

In summary, this study provides policymakers, waste management professionals, and academics with a vital resource for the Green Riyadh Initiative's environmental impacts. It emphasises sustainability and environmental responsibility by offering data-driven recommendations for optimising Riyadh's MSW management systems. This research supports the city's resilience and sustainability efforts, demonstrating that sustainable waste management can improve the environment. Furthermore, this study can serve as a model for other emerging green and smart cities. Its methodology and findings can be applied to similar urban environments worldwide with ambitious sustainability and smart city goals. This study shows how tailored waste management strategies can reduce environmental impacts, setting a precedent for advanced, sustainable practices in urban planning and infrastructure development, ultimately creating more sustainable cities worldwide.

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References

1. Al-Salem, S.M.; Evangelisti, S.; Lettieri, P. Life Cycle Assessment of Alternative Technologies for Municipal Solid Waste and Plastic Solid Waste Management in the Greater London Area. *Chem. Eng. J.* **2014**, *244*, 391–402. [\[CrossRef\]](#)
2. Wang, D.; He, J.; Tang, Y.T.; Higgitt, D.; Robinson, D. Life Cycle Assessment of Municipal Solid Waste Management in Nottingham, England: Past and Future Perspectives. *J. Clean. Prod.* **2020**, *251*, 119636. [\[CrossRef\]](#)
3. Yaman, C.; Anil, I.; Alagha, O. Potential for Greenhouse Gas Reduction and Energy Recovery from MSW through Different Waste Management Technologies. *J. Clean. Prod.* **2020**, *264*, 121432. [\[CrossRef\]](#)
4. *The World Bank Trends in Solid Waste Management*; The World Bank: Washington, DC, USA, 2020.
5. Esfilar, R.; Bagheri, M.; Golestani, B. Technoeconomic Feasibility Review of Hybrid Waste to Energy System in the Campus: A Case Study for the University of Victoria. *Renew. Sustain. Energy Rev.* **2021**, *146*, 111190. [\[CrossRef\]](#)
6. Chisholm, J.M.; Zamani, R.; Negm, A.M.; Said, N.; Abdel daïem, M.M.; Dibaj, M.; Akrami, M. Sustainable Waste Management of Medical Waste in African Developing Countries: A Narrative Review. *Waste Manag. Res.* **2021**, *39*, 1149–1163. [\[CrossRef\]](#)
7. Radwan, N.; Khan, N.A.; Elmanfaloty, R.A.G. Optimization of Solid Waste Collection Using RSM Approach, and Strategies Delivering Sustainable Development Goals (SDG's) in Jeddah, Saudi Arabia. *Sci. Rep.* **2021**, *11*, 16612. [\[CrossRef\]](#)

8. Ouda, O.K.M.; Raza, S.A.; Al-Waked, R.; Al-Asad, J.F.; Nizami, A.S. Waste-to-Energy Potential in the Western Province of Saudi Arabia. *J. King Saud. Univ. Eng. Sci.* **2017**, *29*, 212–220. [\[CrossRef\]](#)
9. Nizami, A.S.; Rehan, M.; Waqas, M.; Naqvi, M.; Ouda, O.K.M.; Shahzad, K.; Miandad, R.; Khan, M.Z.; Syamsiro, M.; Ismail, I.M.I.; et al. Waste Biorefineries: Enabling Circular Economies in Developing Countries. *Bioresour. Technol.* **2017**, *241*, 1101–1117. [\[CrossRef\]](#)
10. Holmberg, T.; Ideland, M. The Circular Economy of Food Waste: Transforming Waste to Energy through ‘Make-up’ Work. *J. Mater. Cult.* **2021**, *26*, 344–361. [\[CrossRef\]](#)
11. Xu, F.; Li, Y.; Ge, X.; Yang, L.; Li, Y. Anaerobic Digestion of Food Waste—Challenges and Opportunities. *Bioresour. Technol.* **2018**, *247*, 1047–1058. [\[CrossRef\]](#)
12. Zhang, J.; Gu, D.; Chen, J.; He, Y.; Dai, Y.; Loh, K.C.; Tong, Y.W. Assessment and Optimization of a Decentralized Food-Waste-to-Energy System with Anaerobic Digestion and CHP for Energy Utilization. *Energy Convers. Manag.* **2021**, *228*, 113654. [\[CrossRef\]](#)
13. Ilgin, M.A.; Gupta, S.M. Environmentally Conscious Manufacturing and Product Recovery (ECMPRO): A Review of the State of the Art. *J. Environ. Manag.* **2010**, *91*, 563–591. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Silva, D.A.L.; Nunes, A.O.; Moris, A.O.; Piekarski, C.M.; Rodrigues, T.O. How Important Is the LCA Software Tool You Choose? Comparative Results from GaBi, OpenLCA, SimaPro and Umberto. In Proceedings of the VII Conferencia Internacional de Análisis de Ciclo de Vida en Latinoamérica, Medellin, Colombia, 10–15 June 2017.
15. Algren, M.; Fisher, W.; Landis, A.E. Machine Learning in Life Cycle Assessment. In *Data Science Applied to Sustainability Analysis*; Elsevier: Amsterdam, The Netherlands, 2021.
16. Directive, E.C. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives. *Off. J. Eur. Union L* **2008**, *312*, 22.
17. Dastjerdi, B.; Strezov, V.; Kumar, R.; He, J.; Behnia, M. Comparative Life Cycle Assessment of System Solution Scenarios for Residual Municipal Solid Waste Management in NSW, Australia. *Sci. Total Environ.* **2021**, *767*, 144355. [\[CrossRef\]](#)
18. Zhou, Z.; Tang, Y.; Dong, J.; Chi, Y.; Ni, M.; Li, N.; Zhang, Y. Environmental Performance Evolution of Municipal Solid Waste Management by Life Cycle Assessment in Hangzhou, China. *J. Environ. Manag.* **2018**, *227*, 23–33. [\[CrossRef\]](#)
19. Silva, V.; Contreras, F.; Bortoleto, A.P. Life-Cycle Assessment of Municipal Solid Waste Management Options: A Case Study of Refuse Derived Fuel Production in the City of Brasilia, Brazil. *J. Clean. Prod.* **2021**, *279*, 123696. [\[CrossRef\]](#)
20. Khandelwal, H.; Thalla, A.K.; Kumar, S.; Kumar, R. Life Cycle Assessment of Municipal Solid Waste Management Options for India. *Bioresour. Technol.* **2019**, *288*, 121515. [\[CrossRef\]](#)
21. Mandpe, A.; Bhattacharya, A.; Paliya, S.; Pratap, V.; Hussain, A.; Kumar, S. Life-Cycle Assessment Approach for Municipal Solid Waste Management System of Delhi City. *Environ. Res.* **2022**, *212*, 113424. [\[CrossRef\]](#)
22. Ahmed, A.T.; Alluqmani, A.E. Management Options and Life Cycle Assessment of Municipal Solid Waste in Madinah, KSA. In Proceedings of the 19th International Conference on Wastewater Treatment and Water Quality, Dubai, United Arab Emirates, 8–9 April 2017; pp. 8–9.
23. Almadhi, A.; Abdelhadi, A.; Alyamani, R. Moving from Linear to Circular Economy in Saudi Arabia: Life-Cycle Assessment on Plastic Waste Management. *Sustainability* **2023**, *15*, 10450. [\[CrossRef\]](#)
24. Mosbah, E.B.; Alsanad, M.A.; Sassine, Y.N. Assessment of Environmental and Economic Impacts of Municipal Solid Wastes Management System: A Case Study. *J. Ecol. Eng.* **2022**, *23*, 137–145. [\[CrossRef\]](#)
25. Aldhafeeri, Z.; Alhazmi, H. Sustainability Assessment of Municipal Solid Waste in Riyadh, Saudi Arabia, in the Framework of Circular Economy Transition. *Sustainability* **2022**, *14*, 5093. [\[CrossRef\]](#)
26. Feil, A.; Pretz, T. Mechanical Recycling of Packaging Waste. In *Plastic Waste and Recycling*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 283–319.
27. Ouda, O.K.M.; Cekirge, H.M.; Raza, S.A.R. An Assessment of the Potential Contribution from Waste-to-Energy Facilities to Electricity Demand in Saudi Arabia. *Energy Convers. Manag.* **2013**, *75*, 402–406. [\[CrossRef\]](#)
28. Aldhubaib, H.A. Electrical Energy Future of Saudi Arabia: Challenges and Opportunities. *Front. Energy Res.* **2022**, *10*, 1005081. [\[CrossRef\]](#)
29. Freidrich, J.; Ge, M.; Pickens, A. *This Interactive Chart Shows Changes in the World's Top 10 Emitters*; World's Top Emitters Interactive Chart I World Resources Institute (wri.org); World Resources Institute: Washington, DC, USA, 2020; Volume 10.
30. AlOboudi, S.M. NAJD, The Heart of Arabia. *Arab. Stud. Q.* **2015**, *37*, 282–299.
31. Saudi Census. The Total Resident Population Count by Region in KSA. Available online: <https://portal.saudicensus.sa/portal/public/1/15/45?type=DASHBOARD> (accessed on 5 February 2024).
32. Alhefnawi, M.A.M.; Lawal Dano, U.; Alshaikh, A.M.; Abd Elghany, G.; Almusallam, A.A.; Paraman, S. Population Modeling and Housing Demand Prediction for the Saudi 2030 Vision: A Case Study of Riyadh City. *Int. J. Hous. Mark. Anal.* **2023**, *ahead-of-print*. [\[CrossRef\]](#)
33. Riyadh General Directorate of Hygiene Riyadh Municipality. Available online: https://clean.alriyadh.gov.sa/Pages/Landfill_definition.aspx (accessed on 22 April 2022).
34. Royal Commission for Riyadh City. *A Comprehensive Strategy for Waste Management in Riyadh*; Royal Commission for Riyadh City: Riyadh, Saudi Arabia, 2016.
35. ISO 14040; Environmental Management: Life Cycle Assessment; Principles and Framework. ISO: Geneva, Switzerland, 2006.

36. ISO 14044; Environmental Management: Life Cycle Assessment; Requirements AnFramework.Nes. ISO: Geneva, Switzerland, 2006.
37. Vigon, B.W.; Tolle, D.A.; Cornaby, B.W.; Latham, H.C.; Harrison, C.L.; Hunt, R.G.; Sellers, J.D. *Life-Cycle Assessment: Inventory Guidelines and Principles* (EPA/600/R-92/245); Risk Reduction Engineering Laboratory, U.S. EPA: Cincinnati, OH, USA, 1993.
38. SGI Initiatives Waste Management Transformation in Riyadh Initiative. Available online: <https://www.greeninitiatives.gov.sa/sgi-initiatives/> (accessed on 1 July 2024).
39. Almutairi, A. Combined Nearest Greedy Algorithm with Randomized Iterated Greedy Algorithm to Solve Waste Collection Problem. *Int. J. Stat. Probab.* **2020**, *9*, 1–66. [\[CrossRef\]](#)
40. Osra, F.A.; Ozcan, H.K.; Alzahrani, J.S.; Alsoufi, M.S. Municipal Solid Waste Characterization and Landfill Gas Generation in Kakia Landfill, Makkah. *Sustainability* **2021**, *13*, 1462. [\[CrossRef\]](#)
41. Ouda, O.K.M.; Raza, S.A.; Nizami, A.S.; Rehan, M.; Al-Waked, R.; Korres, N.E. Waste to Energy Potential: A Case Study of Saudi Arabia. *Renew. Sustain. Energy Rev.* **2016**, *61*, 328–340. [\[CrossRef\]](#)
42. THINKSTEP, G. GaBi Professional, Thinkstep, Leinfelden-Echterdingen, Germany. 2018. Available online: <https://thinkstep.com/software/gabi-software/gabi-professional> (accessed on 3 December 2018).
43. Simon, F.G.; Scholz, P. Assessment of the Long-Term Leaching Behavior of Incineration Bottom Ash: A Study of Two Waste Incinerators in Germany. *Appl. Sci.* **2023**, *13*, 13228. [\[CrossRef\]](#)
44. Cho, B.H.; Nam, B.H.; An, J.; Youn, H. Municipal Solid Waste Incineration (MSWI) Ashes as Construction Materials-a Review. *Materials* **2020**, *13*, 3143. [\[CrossRef\]](#)
45. Kushwaha, A.; Mishra, V.; Gupta, V.; Goswami, S.; Gupta, P.K.; Singh, L.K.; Gupta, C.B.; Rakshit, K.; Goswami, L. Anaerobic Digestion as a Sustainable Biorefinery Concept for Waste to Energy Conversion. In *Waste-to-Energy Approaches Towards Zero Waste*; Elsevier: Amsterdam, The Netherlands, 2022.
46. Hadidi, L.A.; Omer, M.M. A Financial Feasibility Model of Gasification and Anaerobic Digestion Waste-to-Energy (WTE) Plants in Saudi Arabia. *Waste Manag.* **2017**, *59*, 90–101. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Nizami, A.S.; Rehan, M.; Ouda, O.K.M.; Shahzad, K.; Sadeq, Y.; Iqbal, T.; Ismail, I.M.I. An Argument for Developing Waste-to-Energy Technologies in Saudi Arabia. *Chem. Eng. Trans.* **2015**, *45*, 337–342. [\[CrossRef\]](#)
48. Jingura, R.M.; Kamusoko, R. Optimization of biogas production by anaerobic co-digestion. In *Valorization of Lignocellulosic Biomass in a Biorefinery*; Nova Science Publishers, Inc.: Hauppauge, NY, USA, 2016.
49. Pressley, P.N.; Levis, J.W.; Damgaard, A.; Barlaz, M.A.; DeCarolis, J.F. Analysis of Material Recovery Facilities for Use in Life-Cycle Assessment. *Waste Manag.* **2015**, *35*, 307–317. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Gaurh, P.; Pramanik, H. Studies on Pyrolysis of Plastic Wastes Polyethylene to Valuable Hydrocarbons to Minimize Plastic Wastes Load to Environment. In Proceedings of the 66th Annual Session of Indian Institute of Chemical Engineers Hosted at Institute of Chemical Technology, Mumbai, India, 27–30 December 2013; pp. 27–30.
51. Schmidt, A. *Gaining Benefits from Discarded Textiles: LCA of Different Treatment Pathways*; Nordic Council of Ministers: Copenhagen, Denmark, 2016.
52. Gaines, L.L.; Mintz, M.M. *Energy Implications of Glass-Container Recycling*; Argonne National Lab. (ANL): Argonne, IL, USA; National Renewable Energy Lab. (NREL): Golden, CO, USA, 1994.
53. Wäger, P.A.; Hirschier, R. Life Cycle Assessment of Post-Consumer Plastics Production from Waste Electrical and Electronic Equipment (WEEE) Treatment Residues in a Central European Plastics Recycling Plant. *Sci. Total Environ.* **2015**, *529*, 158–167. [\[CrossRef\]](#)
54. Erses Yay, A.S. Application of Life Cycle Assessment (LCA) for Municipal Solid Waste Management: A Case Study of Sakarya. *J. Clean. Prod.* **2015**, *94*, 284–293. [\[CrossRef\]](#)
55. Evangelisti, S.; Lettieri, P.; Borello, D.; Clift, R. Life Cycle Assessment of Energy from Waste via Anaerobic Digestion: A UK Case Study. *Waste Manag.* **2014**, *34*, 226–237. [\[CrossRef\]](#)
56. Williams, A.S. *Life Cycle Analysis: A Step by Step Approach*; TR Series, TR-040; Illinois Sustainable Technology Center: Champaign, IL, USA, 2009.
57. Vinitaskaia, N.; Zaikova, A.; Deviatkin, I.; Bachina, O.; Horttanainen, M. Life Cycle Assessment of the Existing and Proposed Municipal Solid Waste Management System in Moscow, Russia. *J. Clean. Prod.* **2021**, *328*, 129407. [\[CrossRef\]](#)
58. Fei, X.; Jia, W.; Chen, T.; Ling, Y. Life-Cycle Assessment of Two Food Waste Disposal Processes Based on Anaerobic Digestion in China. *J. Clean. Prod.* **2021**, *293*, 126113. [\[CrossRef\]](#)
59. Pujara, Y.; Govani, J.; Patel, H.T.; Pathak, P.; Mashru, D.; Ganesh, P.S. Quantification of Environmental Impacts Associated with Municipal Solid Waste Management in Rajkot City, India Using Life Cycle Assessment. *Environ. Adv.* **2023**, *12*, 100364. [\[CrossRef\]](#)
60. Rana, R.; Ganguly, R.; Gupta, A.K. Life-Cycle Assessment of Municipal Solid-Waste Management Strategies in Tricity Region of India. *J. Mater. Cycles Waste Manag.* **2019**, *21*, 606–623. [\[CrossRef\]](#)
61. Zaman, A.U. Comparative Study of Municipal Solid Waste Treatment Technologies Using Life Cycle Assessment Method. *Int. J. Environ. Sci. Technol.* **2010**, *7*, 225–234. [\[CrossRef\]](#)
62. Gunamantha, M.; Sarto. Life Cycle Assessment of Municipal Solid Waste Treatment to Energy Options: Case Study of KARTA-MANTUL Region, Yogyakarta. *Renew. Energy* **2012**, *41*, 277–284. [\[CrossRef\]](#)
63. Tabata, T. Waste-to-Energy Incineration Plants as Greenhouse Gas Reducers: A Case Study of Seven Japanese Metropolis. *Waste Manag. Res.* **2013**, *31*, 1110–1117. [\[CrossRef\]](#) [\[PubMed\]](#)

64. Ascher, S.; Li, W.; You, S. Life Cycle Assessment and Net Present Worth Analysis of a Community-Based Food Waste Treatment System. *Bioresour. Technol.* **2020**, *305*, 123076. [[CrossRef](#)] [[PubMed](#)]
65. Valenti, F.; Liao, W.; Porto, S.M.C. Life Cycle Assessment of Agro-Industrial by-Product Reuse: A Comparison between Anaerobic Digestion and Conventional Disposal Treatments. *Green Chem.* **2020**, *22*, 7119–7139. [[CrossRef](#)]
66. Slorach, P.C.; Jeswani, H.K.; Cuéllar-Franca, R.; Azapagic, A. Environmental and Economic Implications of Recovering Resources from Food Waste in a Circular Economy. *Sci. Total Environ.* **2019**, *693*, 133516. [[CrossRef](#)] [[PubMed](#)]
67. Liikanen, M.; Havukainen, J.; Viana, E.; Horttanainen, M. Steps towards More Environmentally Sustainable Municipal Solid Waste Management—A Life Cycle Assessment Study of São Paulo, Brazil. *J. Clean. Prod.* **2018**, *196*, 150–162. [[CrossRef](#)]
68. Wang, W.; Tian, S.; Long, J.; Liu, J.; Ma, Q.; Xu, K.; Zhang, Z. Investigation and Evaluation of Flue Gas Pollutants Emission in Waste-to-Energy Plant with Flue Gas Recirculation. *Atmosphere* **2022**, *13*, 1016. [[CrossRef](#)]

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