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Sustainability Assessment of Municipal Solid Waste in Riyadh, Saudi Arabia, in the Framework of Circular Economy Transition

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Abstract: Life cycle assessment (LCA) tools can be used for the environmental assessment of municipal solid waste management (MSWM) systems. The present study aims to evaluate the impact of an MSWM system in Riyadh, Saudi Arabia, under three different scenarios based on the Strategy for 2045 of Riyadh. The current scenario (S0) considers that municipal solid waste (MSW) is landfilled, scenario one (S1) considers waste to energy (WtE) as the main treatment while dry recyclables and organic waste collection schemes are introduced, and scenario two (S2) considers dry recyclables and organic waste collection schemes at the maximum level while the residual portion is treated as WtE. The system boundaries include MSW treatment and disposal by recycling, incineration, composting, and landfilling methods. The scenarios were compared using SimaPro 9.1.1.1 software, and the ReCiPe 2016 Midpoint (H) V1.04/World (2010) H method was used to assess global warming, ozone formation (human health), fine particulate matter formation, terrestrial acidification, freshwater eutrophication, mineral resource scarcity, and fossil resource scarcity. S0 was found to be the scenario with the least impact if considering just the waste treatment. However, S1 and S2 allow material and energy recovery that avoids the impact of obtaining primary resources. S1 and S2 reduced greenhouse gases (GHG) emissions by 55% and 58%, respectively, compared to S0. According to the SV2030, 2% of the electricity generated by the Kingdom would have to come from WtE, but based on the calculations, the maximum electricity from waste would be obtained with S1 fully implemented and would contribute a maximum of 1.51% to Saudi Arabia's electricity demand. This study contributes by providing useful insights that could help decision-makers to understand the potential environmental impacts by assessing each step considered by the Strategy for 2045 for Riyadh along with the consequences on material and energy supply by using the material and energy potential of MSW.

Keywords: municipal solid waste; life cycle assessment; alternative scenarios; landfill; incineration; composting

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1. Introduction

Population growth, urbanization, limited land resources, and insufficient planning policies are restricting waste management efforts in cities [1]. As a result, serious challenges and environmental concerns are mounting due to inefficient systems. This is particularly true among developing countries, where landfilling remains the chosen route due to economic factors or a lack of technical expertise in other options, such as biological and/or thermal treatment [2].

Life cycle assessment (LCA) is a thorough process that evaluates all environmental impacts. As a result, all effects on the environment across the whole life cycle of a product or process are quantified [3]. Although LCA is hardly a scientific tool, it uses a scientific approach for understanding the environmental impacts of products and systems [4]. There is a steady rise in the use of LCA for solid waste management systems, notably in decision-making processes and strategy planning. Utilized since 1995 for sustainable MSW management, LCA is an ideal tool to be applied in MSW management [5]. LCA can evaluate a large variety of factors that affect MSW management, such as geographic location, waste types, energy sources, and the availability of specific disposal alternatives [6,7].

The LCA method has been used in a wide array of research on MSW's environmental impact worldwide. In Nagpur, India, the life cycle assessment (LCA) method has been used to compare landfilling with several treatment options, such as anaerobic digestion, composting, and material recovery facilities (MRF). According to the findings of one study, MRF with anaerobic digestion was found to have less of an impact on the environment when used in conjunction with landfilling and composting [8]. In the study by [9], the authors contrasted open dumping, composting, and landfilling with joint composting, disposal, and landfilling. The final alternative was the most beneficial in all of the impact areas considered. Another study was undertaken in Hangzhou, China, by [10], which compared three treatment options: (i) landfilling with energy recovery, (ii) incineration with energy recovery, and (iii) landfilling without energy recovery. Open landfills are still the preferred method for MSW disposal in developing countries due to the absence of an effective MSW management system. Pyrolysis is commonly used as a waste treatment technology (thermal recycling), which might be a replacement of disposal in landfills [11,12]. Secondary waste (ashes and dusts) originating from municipal waste incineration plants can be used as backfilling material in underground mining projects [13,14].

A lack of waste management systems is a significant problem for developing countries in Asia, Africa, and the Middle East. Inefficient MSW management systems result in several factors, including bad working conditions, budget limits, a lack of precise governing mechanisms, inappropriate use of technology, and a lack of awareness. In addition, the environment, human health, and economy suffer when waste is not properly handled and controlled. As a result, building adaptable and reliable waste management strategies is essential to reducing the quantity of waste being developed by educating residents about waste recycling in addition to employing effective policies and plans for waste management [15,16].

There is high awareness among Saudi officials of the critical demand for solutions to waste management. They have invested millions in solving the problem. The Saudi government in 2017 allocated SAR 54 billion to municipal services, including the waste disposal and drainage system [16,17]. The Saudi government is initiating stronger recycling and waste management activities. It has also recently approved new directives providing for an integrated municipal waste management system. Meanwhile, more serious efforts are needed in the Kingdom to improve the waste management scenario [17]. Among the options are the methodical implementation of waste management strategies, such as materials recovery facilities, energy waste systems, and recycling facilities. These can also greatly enhance the waste management scenario and promote local employment opportunities [18].

KSA's Vision 2030 commits to reducing GHG emissions in order to achieve environmental key performance indicators. Environmental experts point to uncontrolled landfills as one of the largest emitters of GHGs [19].

This study will help decision-makers to understand the potential environmental impacts of each step considered by the Strategy for 2045 for Riyadh, as well as the consequences on material and energy supply by using the material and energy potential of MSW.

2. Materials and Methods

2.1. Study Area

Covering a total area of more than 2800 square kilometers, Riyadh is the capital of the Kingdom of Saudi Arabia and the largest city in the Arabian Peninsula. It has experienced rapid population and areal growth since 1900, with an annual growth rate of more than eight percent [20]. Its population growth was around 2.6 million—from 6 to 8.6 million—over 12 years, from 2007 to 2019 (Figure 1) [21,22]. Population growth led to significant increase the amount of waste generation. Currently, Riyadh city generates 3.4 million tons of municipal solid waste [23].

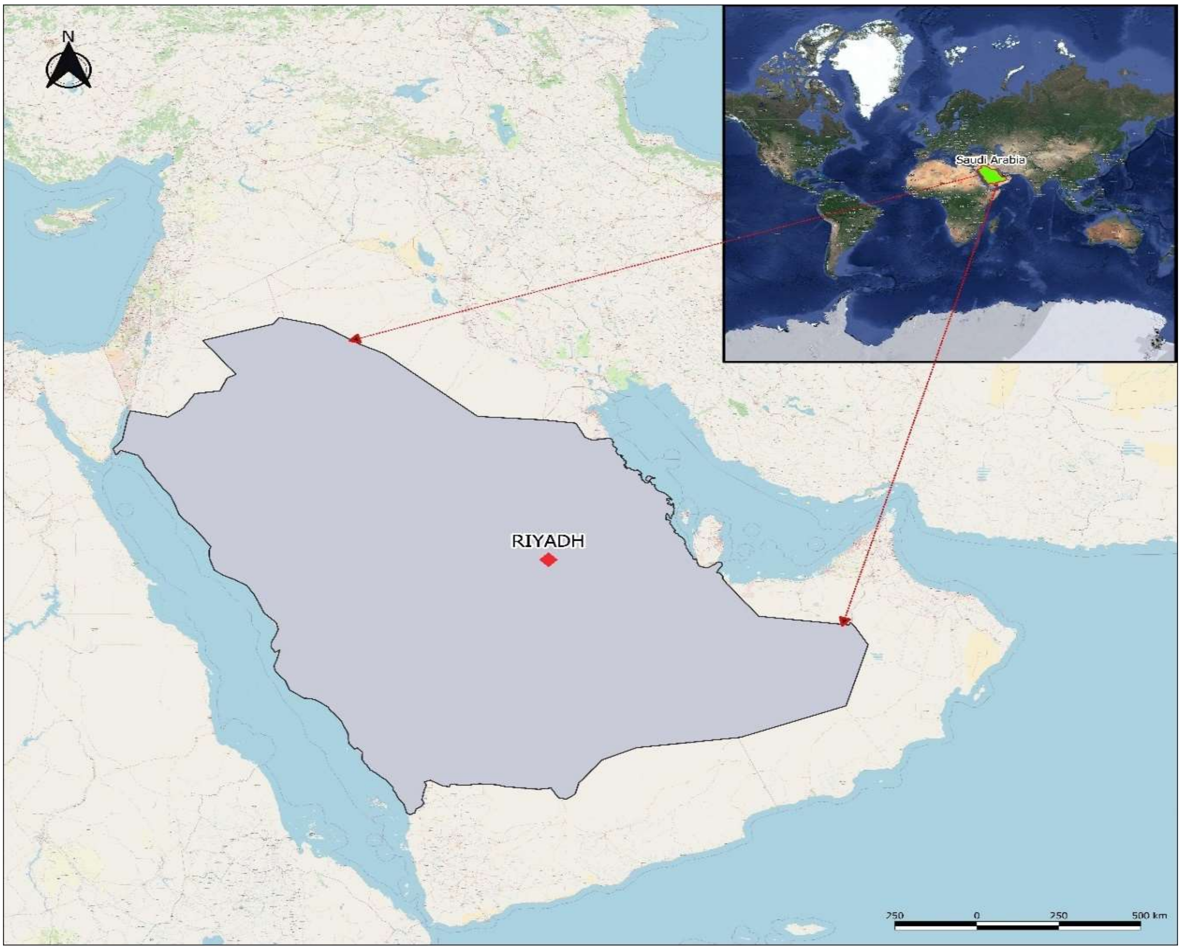

Figure 1. Map of Saudi Arabia showing Riyadh, the study site.

2.2. Scenario Description

The Municipal Waste Management Strategy for 2045 forecasts that, until 2020, all MSW will be mainly landfilled, whereas from then on, residual waste treatment by energy from waste (residual in Table 1) will become the dominant treatment. The intention is to gradually increase the specific management of organic and dry waste (recycling of dry materials).

Table 1. Scenario assumptions.

Waste Management	S0	S1	S2
Landfill	Open landfill: 100%	Landfill with gas and leachate extraction: 2%	Landfill with gas and leachate extraction: 1%
Dry waste recycling	0%	Material recycling (MRF—material recovery facility): 5%	Material recycling (MRF—material recovery facility): 10%
Organic waste management	0%	Composting and anaerobic digestion: 13%	Composting and anaerobic digestion: 21%
Residual waste management	0%	Waste to energy (WtE): 80%	Waste to energy (WtE): 68%

The potential generic MSW treatment options over time for the future management of the city's waste are the following: landfill, dry (recycling of dry materials), organic (organic waste management), and residual (residual waste treatment by energy from waste). Based on the Strategy for 2045, three scenarios were defined and described in Table 1 [24].

S0 (baseline scenario): Waste is collected in an entirely nonselective way and disposed of in an open landfill in Riyadh: Al Sulay Landfill. This is the dominant current MSW disposal method in Riyadh and assumed as the baseline scenario. In fact, in 2016, only approximately 3% of MSW collected was processed by a material recovery facility (MRF) that allowed for the recovery of some paper, plastics, and ferrous as well as nonferrous metals [24]. The municipal solid waste landfill of Riyadh is located about 25 km from the city center, has a total area of 10 million m^2, and is intended for the reception of municipal solid waste only [25].

S1: This scenario corresponds to MSW management in the year 2023 of the Strategy for 2045. It is assumed that 2% of waste will be landfilled, with gas and leachate extraction. According to the Strategy for 2045, at present there is a strong reliance on dump sites/landfills, but they should be modern, fully engineered sites with gas and leachate extraction.

Residual waste is supposed to be incinerated, being the main waste treatment in S1 (80% of the waste). The strategy considers that recycling and organic schemes will be introduced to collect dry recyclables and organic waste, managing 5% and 13% of the waste, respectively.

S2: From the year 2035 to 2045, the proportion of each waste management method will be maintained at the same levels, but the quantity will increase, as waste volumes are expected to increase over time due to the growing population. Therefore, S2 represents both the 2035 and 2045 scenarios. It is expected to increase the dry waste recycling and organic collection schemes to their maximum levels. The proportion of residual WtE will decrease to 68%. Landfills will be maintained as residual management only for materials unsuitable for residual treatment processes and any process residues, such as incineration ash (Figure 2).

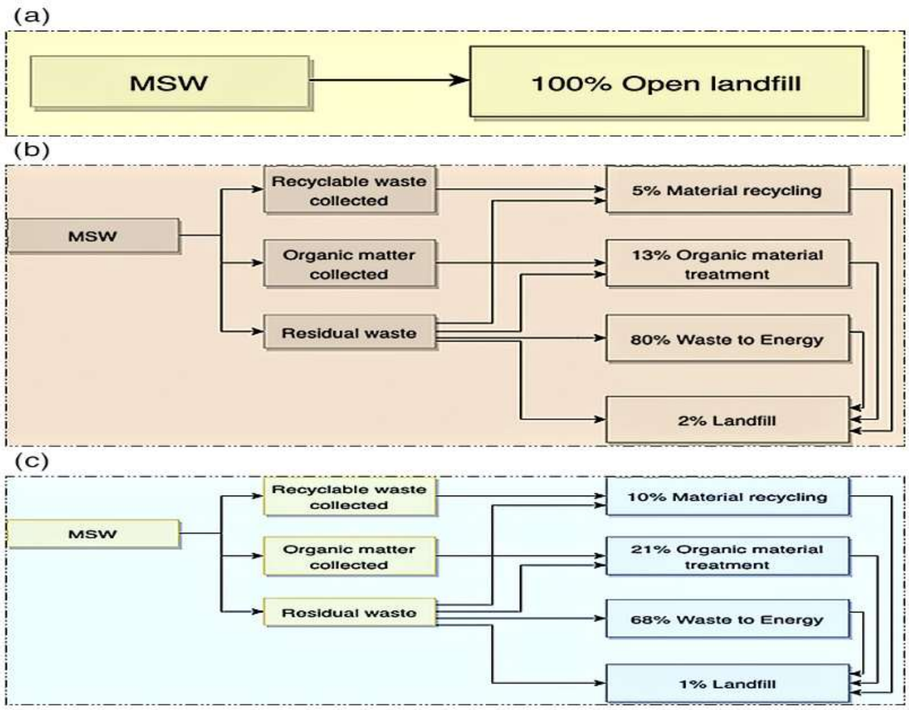

Figure 2. Municipal solid waste (MSW) management systems based on the proposed scenarios under study in Riyadh. (**a**) Scenario 0 (S0), (**b**) scenario 1 (S1), and (**c**) scenario 2 (S2).

2.3. LCA Methodology

An MSW management assessment of the current situation from environmental, economic, and social perspectives through a life cycle approach is the most essential first step before making any decision in order to select the right technologies, developed policies, and strategies that a country can follow [26].

The LCA methodology was used to evaluate and compare the environmental impact of each waste management scenario considered by the Strategy for 2045 for the city of Riyadh. An attributional LCA was conducted according to ISO 14040 [27] and ISO 14044 [28]. Long-term emissions from landfills are particularly relevant in LCA regarding heavy metals and organic waste, which have the potential for pollution and long-term greenhouse gas generation, respectively. Currently, two approaches exist: considering long-term emissions or not doing so. In this case, as the Al Sulay Landfill is an open dump, long-term emissions (>100 years) are considered, as indicated by Doka [29], as excluding long-term emissions landfills is a means to avoid burdens today and move them far into] the future.

End-of-life processes can result in the production of secondary materials or recovered energy. According to [30], the recommended manner to address them in LCA in order to maintain the functional unit in comparative scenarios is by applying system expansion.

Energy recovered in thermal processes can avoid the generation of energy obtained via conventional fuels, as in the case of material recycling, which avoids obtaining materials from virgin sources. Therefore, the LCA was performed according to cut-off modeling, but system expansion was used to present the avoided impact.

The goal of this study is to evaluate and compare the environmental burdens and credits associated with different municipal waste management scenarios in the city of Riyadh based on the Municipal Waste Management Strategy for 2045.

In this study, the functional unit was defined as one ton of municipal solid waste generated in the city of Riyadh.

2.3.1. System Boundaries

The waste composition is indicated in Table 2. Additionally, for the assessment of the repercussions on the carbon footprint related to electricity consumption in Riyadh, the unit used is the absolute MSW generated in the years 2018 and 2020, as well as that forecasted for 2023, 2035, and 2045.

Table 2. Riyadh municipal solid waste composition in 2014 [19,24].

Waste Category	%
Organic matter	57.20
Paper/cardboard	11.60
Plastic	13.00
Metals	2.30
Glass	3.00
Textiles	2.90
Wood	6.60
Others	3.40

Once waste is generated, several sequential activities are required to manage the municipal solid waste, which include at least collection, transportation, and treatment. All the facilities that will be necessary to implement the Strategy for 2045 and changes in waste management operations are based on Strategy for 2045 proposals, and, if required, assumptions are made. For the comparison, the collection and transportation to management is out of the scope, as the facilities will be located in the area surrounding the city, as is the current landfill, so there will be no significant changes between these waste management activities.

Capital goods of the management systems are included in the LCA, and their contribution to certain impact categories may not be negligible [31].

The valorization of secondary products obtained by different treatments, as they can alter the LCA results by their additional environmental benefits outside the system boundaries, is presented separately.

2.3.2. Life Cycle Inventory

Data for the life cycle inventory were obtained from the waste characterization study in Riyadh, the literature, and the Ecoinvent v3.6 database. Moreover, the Ecoinvent v3.6 database was used to obtain the environmental loads associated with the waste treatments considered in this study, with some exceptions detailed in the Assumptions section. Datasets were adapted by using the Saudi Arabian energy mix from the year 2018, which relies primarily on oil. In 2017, the Saudi Arabian government prepared a strategy called the 2030 Vision [32,33].

The objective of the Saudi Vision 2030 (SV2030) is to set up renewable and sustainable energy (RnSE) projects to meet the demand for electricity by increasing the use of renewable resources, reducing the dependency on fossil fuels, and reducing the country's CO_2 emissions. Therefore, when analyzing the results for the period of 2018–2045 (Section 3.2), S2 is modeled based on the SV2030 electricity mix based on the installed capacity proposed, as it represents the scenario of the years 2035 and 2045.

The modeling of the impact of the electricity mix was based on the share of energy sources in accordance with the King Abdullah City for Atomic and Renewable Energy (K.A.CARE) plan. By 2032, King Abdullah City for Atomic and Renewable Energy envisions 9 GW of wind, 1 GW of geothermal, 17.6 GW of nuclear, 41 GW of solar, and 3 GW of WtE sources of clean energy. By 2032, the energy mix will be 41% renewable (12% PV, 19% CSP, 7% wind, 1% geothermal, and 2% WtE), with hydrocarbons accounting for 46%. The carbon footprint of the electrical energy mix is expected to be 0.548 kg CO_2-eq/kWh in 2032, a 51% decrease compared to 2018. It is assumed that the MSW composition is maintained during the period analyzed, from 2018 to 2045.

2.3.3. Assumptions and Calculation Methods

The Strategy for 2045 does not indicate how each MSW fraction is managed in each scenario. As a first step, it was necessary to assign in each scenario the treatment that each fraction would receive, and in which proportion to fulfill the management proposals of the Strategy for 2045.

For each waste treatment option, different considerations and assumptions were made:

Landfill

The open unsanitary landfill in Riyadh, the Al Sulay Landfill, has only waste compaction and daily soil covers, but no bottom liner, no leachate treatment, and no landfill gas capture.

The unsanitary landfill is conditioned by the climate region, depending on the net annual infiltration, which is calculated from the mean annual precipitation (MAP) (mm/year) minus the actual annual evapotranspiration (ETa) (mm/year) [29,34]. According to [35], Saudi Arabia is classified as hyperarid, so the same is assumed for the city of Riyadh.

In S1 and S2, a sanitary landfill with leachate and gas capture is assumed, based on the Ecoinvent database. As a finalist management of the MSW, the benefits obtained from the biogas energy production are not accounted for.

Organic Material Treatment

The Strategy for 2045 indicates that the organic treatment capacity required should be potentially anaerobic digestion (AD). Therefore, it is assumed that in S1 the installed capacity is 50/50 composting and AD, whereas in S2 the ratio is 30/70; the industrial composting of biowaste produces compost while avoiding the production of fertilizer [36].

The anaerobic digestion (AD) of biowaste treatment produces digester sludge and biogas. Regarding the digester, it is assumed that it is used as landfilling, so no substitution or impact allocated are considered. The biogas is assumed to be used in cogeneration, to produce electricity and heat, so it results in avoided impact.

Material Recovery Facility (MRF) and Recycling

The collected MSW, separated in fractions or not, is assumed to be sorted in a sorting plant before the separated fractions are sent to recycling facilities. This first step applies to all dry fractions collected.

According to [26], previous studies on MSW management assumed a substitution ratio set to 1:1 and/or a quality similar to the substituted product; in this study, a quality decrease in the materials recovered using different assumptions is accounted for.

Textile waste sorting and recycling was not available in Ecoinvent, so it was modeled based on inventory data from [37], considering the treatment route of one ton of used cotton textiles discarded by households and organizations from the point of collection to recycling, including the sorting and transport of textiles, as well as shredding.

For glass recycling, according to [38], the total recycling process energy for the case of maximum recycling is about 1934 kWh of natural gas plus 551 kWh of electricity per ton of glass containers. Therefore, based on the consumptions considered in the recycling process and the product obtained, the replacement considers a glass container without cullet.

Plastic recycling is modeled as HDPE based on the average MSW plastic mixture composition, as indicated by [39]. Cardboard and paper are modeled together, considering the sorting and recycling process to produce containerboard. The conventional primary product is made of pulpwood, from hardwood and softwood. Therefore, the raw material to produce 100% recycled and 40% recycled containerboard was compared.

Electronic waste is the waste stream that is growing the fastest, and one of the most substantial elements is electronic plastics [40]. There are great differences among the waste electrical and electronic equipment (WEEE) categories' average mass share of plastics and metals. Most common plastics obtained from WEEE are PP, PS, and ABS, so it is assumed that an average of these plastics is avoided by WEEE recycling.

Regarding metals, it is assumed that the main materials are recycled copper, aluminum, and steel, based on an assumption conducted by [41]. Therefore, the assumption made in this article of only considering copper, aluminum, and steel is considered a conservative scenario in terms of the impact avoided.

Waste to Energy

According to Hadidi et al. (2020), during this period of 2035–2045 the WtE technologies for residual waste in Saudi Arabia may change; for example, different WtE technologies may be applied: mass burn, gasification, plasma arc gasification, anaerobic digestion, refused derived fuel (RDF), and solid recovered fuel (SRF) [11]. In this study, the current technology available is assumed: incineration with energy recovery (heat and electricity) with fly ash extraction.

2.3.4. Life Cycle Impact Assessment Methodology

Numerous studies have demonstrated the significant impacts on human health and ecosystems caused by the release of chemicals, particles, or pathogens from waste management systems [26]. Therefore, in the current study the method used is ReCiPe 2016 Midpoint (H) V1.04/World (2010) H, which considers different perspectives of the impact that the management of MSW in Riyadh can potentially cause [42]. The ReCiPe LCIA method was selected because it provides characterization factors that are representative of the global scale, but also considers country-specific characterization factors, which fits the geographical scope of the study. According to Vitale et al. (2018), the ReCiPe method is the most used method in the context of waste management and the uncertainty of the results is relatively low [43]. The hierarchic (H) perspective was selected for the analysis, as it is considered the most balanced and recommended for use by the method of the three proposed perspectives (Egalitarian, Individualist, and Hierarchist) [44]. SimaPro software (version 9.1.1.1, PRé Sustainability, Amersfoort, The Netherlands) was used to carry out the LCA [45].

3. Results

In this section, the environmental impact of the three scenarios defined are compared for seven impact categories: global warming, ozone formation (human health), fine particulate matter formation, terrestrial acidification, freshwater eutrophication, mineral resource scarcity, and fossil resource scarcity.

The results are presented in Table 3 per waste treatment and scenario, and the detailed results for all the impact categories included in the ReCiPe method are presented in the Supplementary Materials (Table S1).

The results show that S0 was the scenario with the most impact for four of the seven impact categories analyzed: global warming, ozone formation (human health), fine particulate matter formation, and terrestrial acidification. S0 considers that 100% of the MSW collected is landfilled in unsanitary landfills, so it requires fewer resources than the other treatments but emits more gases into the atmosphere related to waste decomposition and particulate matter. S1 reduced the GHG emissions by 55%. This scenario considers that the MSW is 80% managed as residual (WtE), and that dry recyclables and organic waste begin to be treated separately.

S2 reduced the GHG emissions by 58% compared to S0. The higher proportion of waste to recycling and organic treatment instead of WtE (the main treatment in S1) makes S2 the best option for global warming and ozone formation (human health). However, not all impact categories of waste management in S1 and S2 resulted in better environmental performance. Mineral resource scarcity and fossil resource scarcity were increased significantly, as MSW treatments alternative to landfills demand more resources.

For example, for the impact category of fossil resource scarcity, recycling was the treatment with most impact in both S1 and S2, where it constituted 5% and 10%, respectively, of MSW recycling. However, the environmental costs of MSWM can be compensated for by the impact avoided outside the system, which is analyzed in Section 3.1.

Table 4 shows the contribution of each fraction to the environmental impact in the three scenarios assessed, which differ from the MSW composition. In S0, the contribution to the impact is highly related to the MSW characterization, as all waste is managed the same way, in unsanitary landfills. Organic matter, which was 57.20% of the MSW, was the fraction with most impact in all impact categories, from 54.71% for fine particulate matter formation to 87.59% for freshwater eutrophication.

In S1, the linear relation with the MSW composition did not occur so clearly. It has to be considered that waste (all fractions) is mainly incinerated, and the fraction that goes to a landfill is conducted in a sanitary landfill with gas and leachate capture. Organic matter continued to be the fraction with most impact as the most relevant fraction in terms of characterization, with a contribution to the impact ranging from 31.19% (fossil resource scarcity) to 72.92% (freshwater eutrophication).

S1 considers that plastic is mainly incinerated. It represented 13% of the MSW weight but was responsible of almost half of the GHG emissions of MSW in S1 (49.19%).

Metals and glass are partially collected separately and recycled. This means that even though metals represented 2.3% of the MSW composition and glass 3%, they were very relevant to categories related to resource scarcity. Textiles are incinerated in S1, which makes textile waste relevant to categories related to air pollution, such as ozone formation (human health) and fine particulate matter formation, with 22.50% and 11.90% of the impact, respectively.

Table 3. Results for 1 ton of MSW collected (FU).

Impact Category	Units	Landfill			Organic Treatment			Recycling			WtE			Total		
		S0	**S1**	**S2**	**S0**	**S1**	**S2**	**S0**	**S1**	**S2**	**S0**	**S1**	**S2**	**S0**	**S1**	**S2**
Global warming	kg CO_2 eq	1294.34	3.22	0.14	0	10.38	17.53	0	29.1	57	0	537.25	469.02	1294.34	579.95	543.68
Ozone formation, human health	kg NOx eq	1.08	0.0018	0.001	0	0.0112	0.0169	0	0.044	0.087	0	0.35	0.28	1.08	0.41	0.38
Fine particulate matter formation	kg PM2.5 eq	13.2	0.00062	0.00033	0	0.0178	0.0224	0	0.031	0.06	0	0.06	0.05	13.2	0.11	0.13
Terrestrial acidification	kg SO_2 eq	0.42	0.0014	0.00069	0	0.1072	0.1175	0	0.08	0.15	0	0.17	0.14	0.42	0.35	0.4
Freshwater eutrophication	kg P eq	0.0044	0.0001	0.000042	0	0.001	0.002	0	0.0022	0.0053	0	0.01	0.01	0.0044	0.02	0.02
Mineral resource scarcity	kg Cu eq	0.0075	0.00088	0.00055	0	0.013	0.02	0	0.051	0.12	0	0.16	0.13	0.0075	0.23	0.27
Fossil resource scarcity	kg oil eq	1.41	0.13	0.073	0	1.28	2.06	0	5.77	11.12	0	5.14	4.22	1.41	12.33	17.47

Table 4. Contribution to the environmental impact of each MSW fraction and contribution to the MSW.

	Organic Matter	**Paper/Cardboard**	**Plastic**	**Metals**	**Glass**	**Textiles**	**Wood**	**Others**
Fraction contribution to the FU per weight	57.20%	11.60%	13.00%	2.30%	3.00%	2.90%	**6.60%**	3.40%
			S0					
Global warming	61.66%	26.84%	1.80%	2.48%	0.01%	2.78%	0.78%	3.66%
Ozone formation, human health	55.45%	11.66%	24.76%	2.23%	0.15%	0.15%	2.31%	3.30%
Fine particulate matter formation	54.71%	11.55%	17.21%	2.20%	2.87%	0.00%	8.20%	3.25%
Terrestrial acidification	55.98%	12.63%	23.25%	2.25%	0.18%	0.17%	2.23%	3.33%
Freshwater eutrophication	87.59%	1.74%	0.47%	3.52%	0.11%	0.11%	1.25%	5.21%
Mineral resource scarcity	57.20%	11.60%	13.00%	2.30%	3.00%	2.90%	6.60%	3.40%
Fossil resource scarcity	57.20%	11.60%	13.00%	2.30%	3.00%	2.90%	6.60%	3.40%

Table 4. *Cont.*

	Organic Matter	Paper/Cardboard	Plastic	Metals	Glass	Textiles	Wood	Others
S1								
Global warming	40.94%	2.00%	49.19%	0.70%	1.24%	3.73%	0.14%	2.06%
Ozone formation, human health	36.62%	7.72%	22.12%	3.05%	3.25%	22.50%	3.06%	1.68%
Fine particulate matter formation	40.57%	8.50%	20.81%	8.41%	6.43%	11.90%	1.95%	1.43%
Terrestrial acidification	50.36%	4.56%	18.87%	6.33%	5.55%	11.67%	1.54%	1.12%
Freshwater eutrophication	72.92%	2.88%	6.49%	9.83%	1.26%	1.66%	1.83%	3.12%
Mineral resource scarcity	41.86%	7.02%	22.87%	11.52%	2.86%	8.31%	3.84%	1.72%
Fossil resource scarcity	31.19%	3.85%	25.99%	10.18%	19.60%	6.25%	1.25%	1.68%
S2								
Global warming	37.42%	3.24%	49.31%	1.27%	2.25%	3.36%	0.15%	2.99%
Ozone formation, human health	33.71%	7.24%	25.70%	5.15%	5.48%	16.34%	3.23%	3.14%
Fine particulate matter formation	33.55%	8.65%	23.27%	11.83%	8.81%	8.49%	1.63%	3.76%
Terrestrial acidification	43.44%	3.65%	22.19%	9.44%	8.18%	8.72%	1.34%	3.03%
Freshwater eutrophication	60.98%	2.16%	7.62%	14.87%	1.72%	1.17%	1.69%	9.80%
Mineral resource scarcity	32.07%	4.84%	24.83%	16.12%	3.22%	4.80%	3.23%	10.88%
Fossil resource scarcity	23.78%	2.55%	27.77%	12.05%	23.31%	6.46%	0.89%	3.18%

In S2, the trend observed was similar to that of S1. Organic waste treated separately (composting and anaerobic digestion) increased significantly. This produced a reduction in the impact of the organic matter management, contributing a maximum impact of 60.98% for freshwater eutrophication.

3.1. Benefits from System Expansion

In the previous section we analyzed the environmental impact of MSW management if different treatment strategies are applied.

In this section we include the evaluation of the impact avoided, considering that material recycling, organic treatment, and residual waste to energy provide energy and materials that replace virgin sources. Material recycling, organic treatment, and residual waste to energy have repercussions for material and energy obtention and availability. When assessing MSWM, we need to consider not only the impact of the treatment itself but also the benefits beyond the system.

Figure 3 shows the avoided and net impact of applying system expansion for the impact categories and scenarios assessed, with the avoided impact being the benefits of replacing primary sources (materials and fuels), whereas the net impact shows the difference between the treatment impact and the benefits from the replacement of sources.

For all impact categories, the avoided impact from the replacement of resources compensated for the impact of the waste treatment in S1 and S2. S1 and S2 are better options than the current satiation, as they allow for the reintroduction of secondary materials and energy into the economy. The net impact of S1 and S2 was negative for all categories, which means that the benefits are higher than the impact caused by the waste treatment itself.

S2 considers a higher contribution of dry waste to recycling and organic treatment than S1, which considers the incineration of almost all types of waste. This difference makes S2 a better option than S1, as it is aligned with circular economy principles, where the material recovery is preferable to the energy recovery. The environmental impact for each scenario and impact category of treating 1 ton of MSW collected (FU), the avoided impact, and the net impact, considering system expansion, are detailed in the Supplementary Materials (Table S2).

3.2. GHG Emissions of the MSW Treatment in Riyadh for the Period 2018–2045

In this section, we evaluate the global warming potential of MSW treatment in Riyadh over the years for the period 2018–2045. Instead of presenting the results per 1 ton of MSW (FU), we present the results for the total annual MSW generation in the city. The city of Riyadh generated 3.4 million tons of MSW in 2018 and 3.7 million tons in 2020. As the population is expected to increase at an annual growth rate of 3.5%, the MSW generation is expected to increase as well.

In this section, the MSW generated in Riyadh, the absolute GHG emissions, and the net emissions, if considering system expansion, are considered. The Riyadh Strategy for 2045 forecasts that by 2045 the MSW generation in Riyadh city will be 5 million tons. Therefore, a linear relation between the latest available MSW generation data (2020) and the 2045 MSW generation data in Riyadh was calculated to define the annual waste generation.

S0, analyzed in this article, is representative of the 2018 situation, where almost all MSW was landfilled. S1 represents the year 2023 situation, and S2 represents the 2035 and 2045 scenarios.

SV2030 considers installed electricity power less dependent on fossil fuels and with a lower carbon footprint. Therefore, S2 was recalculated considering that, for the period 2035–2045, the electricity grid mix will be the one proposed by SV2030. During this period, waste treatment processes consuming electricity and electricity substitution will have a carbon footprint of 0.548 kg CO_2-eq/kWh, instead of the 2018 mix of 1.113 kg CO_2-eq/kWh (modeled using the Ecoinvent v3.6 dataset and calculated with the ReCiPe 2016 Midpoint (H) method). The GHG emissions of electricity in the period 2035–2045 is 51% lower than those of the 2018 grid mix.

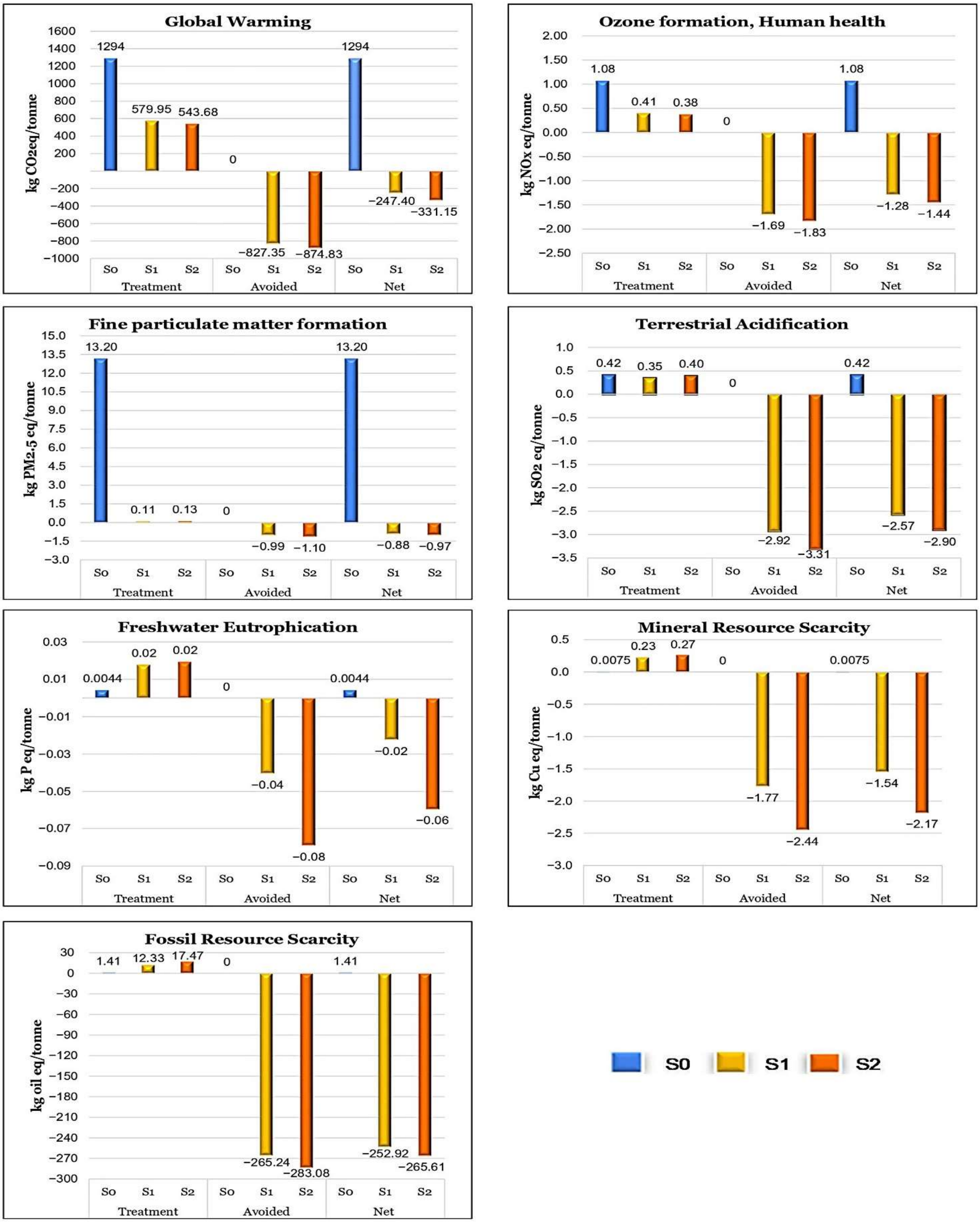

Figure 3. Global warming, ozone formation (human health), fine particulate matter formation, terrestrial acidification, freshwater eutrophication, mineral resource scarcity, and fossil resource scarcity potential of treating 1 ton of MSW collected (FU), the avoided impact beyond the system, and the net impact, considering system expansion for each scenario.

Figure 4 shows the evolution of the impact of MSW management on global warming (treatment impact and net impact) in Riyadh over the years based on the scenarios considered and the amount of waste generated. The transition from unsanitary landfills (S0) to waste management alternatives (S1 completely implemented in 2023 and S2 in 2035) will immediately reduce the carbon emissions of MSW treatment. With energy and material recovery, and considering system expansion, we can obtain negative GHG emissions if S1 is fully implemented in 2023 (negative net impact).

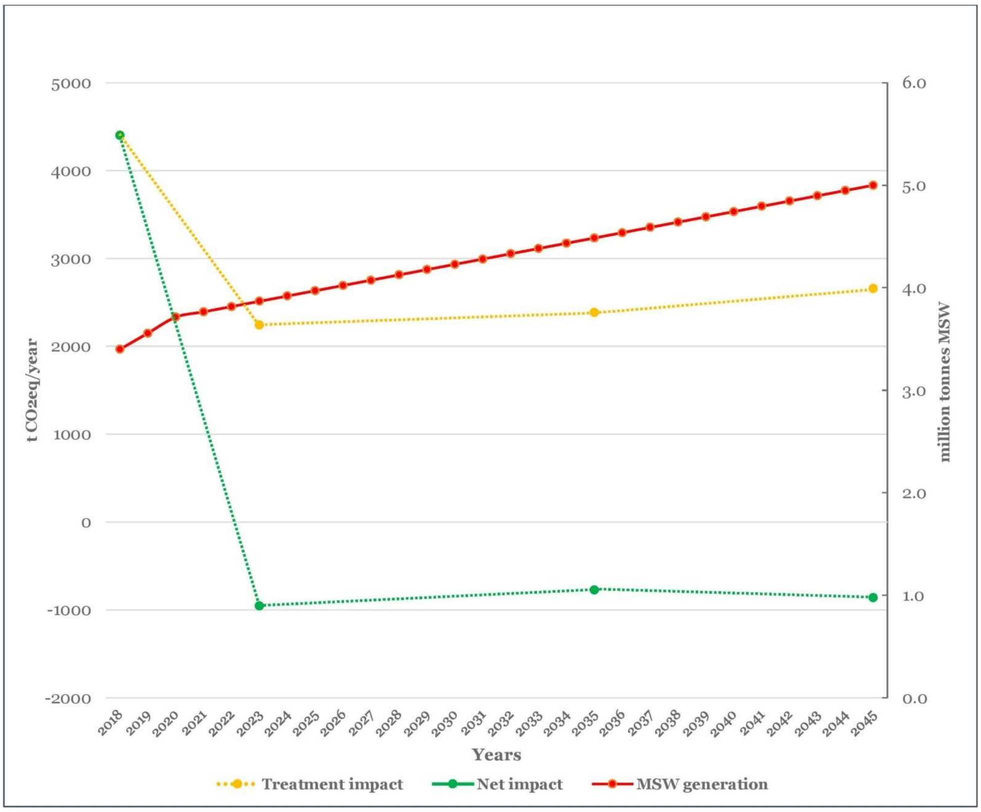

Figure 4. Estimated MSW amount and GHG emissions (treatment and net) through 2018 to 2045.

The minimum impact of MSW treatment will be reached by 2023. At S1 in 2023, the emissions will increase again if the generation of MSW continues to increase. Consequently, the net impact will increase, as the electric grid mix will already contain a high share of sources that are not based on fossil fuels.

From 2035 to 2045, with S2 fully implemented, the net impact will decrease the more MSW is generated, as the benefits beyond the system would be more important than the impact of the treatment itself.

3.3. *Electricity Obtained from MSW in Riyadh*

SV2030 plans to obtain 2% of electricity from WtE. In this section, we want to validate whether, by implementing the Riyadh Strategy for the period 2018–2045, this 2% can be reached, and, if so, in what particular year.

In Saudi Arabia in 2020, households consumed nearly 50% of the overall electricity, most of it generated from oil. Hence, the residential sector that produces MSW can also contribute to energy production and emissions savings.

In the Riyadh region, the 2019 electricity consumption of households was 40,748,603 MWh, and the population was 8,660,885 [46]. This means that the annual electricity consumption in households is 4700 kWh per capita per year. Riyadh's demographics are projected to expand to 15–20 million people by 2030, standing at an annual growth rate of 3.5% [47].

As assumed in Section 3.2, S1 represents the year 2023 situation, whereas S2 represents those of 2035 and 2045. In order to calculate the population for 2023, 2035, and 2045, when the scenarios are fully implemented, an annual growth rate of 3.5% was applied based on the 2019 situation.

The electricity from waste is generated by incineration and anaerobic digestion, resulting in the production of electricity and heat that in turn replaces fossil fuels as a source for energy production. An average electricity generation of 383 kWh per ton of MSW is projected if S1 is fully implemented, and 354 kWh per ton of MSW under S2. Even though anaerobic digestion increases from 6.5% of the total waste in S1 to 14.7% in S2, incineration decreases from 80 to 68%, which explains the reduction in the electricity generated in S2.

WtE produces high-voltage electricity, and households consume low-voltage electricity, so 8% losses from high to low voltage are assumed. The total annual electricity generated from WtE is calculated by considering the annual MSW generation calculated in the previous section.

Figure 5 shows the total household electricity consumption in Riyadh and the electricity that could be produced by MSW treatment. We assume that the energy consumption per household will be maintained during the period 2018–2045. We also assume an increase in the population by an annual growth rate of 3.5%.

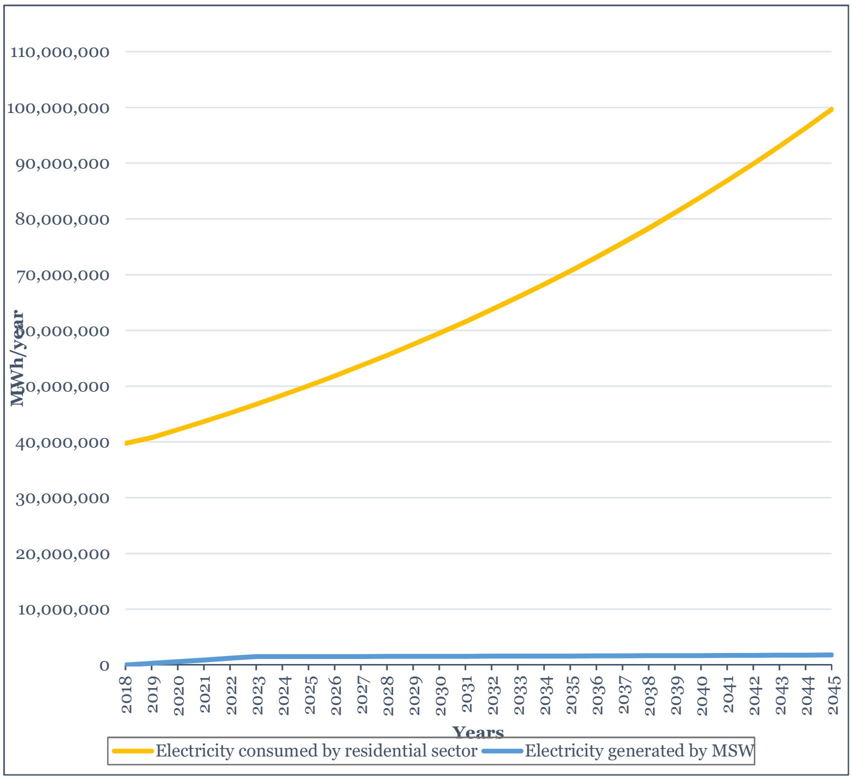

Figure 5. Amount of annual energy consumed by households in Riyadh and that produced by MSW.

In 2023, WtE could cover 3.17% of the electricity demanded by households, whereas in 2035 it would represent 2.25%. In 2045 it would be 1.78%. In 2023, S1 would be fully implemented, and in 2035 S2 would be. According to the calculations and results obtained, the SV2030 could be reached if considering only the residential sector's electricity demand, but not all demand. In the year 2020, the electricity demanded by the residential sector in Saudi Arabia was 48% [48]. If the maximum that WtE can provide is 3.17% of the residential demand, it would be 1.51% of the total electricity demand of Saudi Arabia electricity, which is near to the goal of SV2030.

3.4. Key Limitations

Waste collection highly depends on consumers' behavior, as they have a large influence on the fractions that will progress to the treatment stage. Additionally, sorting facilities have a large influence on the quality of secondary products obtained from recovery facilities. These variables were not assessed in the study and could have had an influence on the final results.

Waste treatment was modeled by using secondary data, the Ecoinvent database, as specific data from the type of technology that will be implemented, because existing facilities in Riyadh are not available. Even with this being the case, waste treatment technology datasets have been adapted to the local conditions, i.e., electricity inputs in datasets were modified to be representative of the reality of Saudi Arabia (electricity mix for the year 2018 and the Vision 2030 guidelines).

The MSW generation, population, and electricity consumption for the period 2018–2045 were calculated based on Riyadh Strategy forecasts and governmental statistics. Therefore, it is expected that the results may vary over time if any of these criteria (waste generation, population, and electricity consumption) change. The results for the period 2035–2045 consider that the electricity mix will be the one stated by SV2030. Any variation in the plan or its implementation may influence the results.

3.5. Future Applications

Regional and country strategic decisions have implications on the environment, society, and the economy. The use of LCA can support decision-makers to consider the environmental consequences of systems—in our case on municipal waste management—to determine the best strategy to implement. Multiple aspects are to be considered, based on an environmental perspective, when choosing the right municipal waste management strategies, including the GHG emissions reduction goals defined by the Kingdom, the salubrity of waste management in crowded cities like Riyadh, its affectation in the population, its economic costs of waste management, and the future costs regarding resource availability.

Our study finding shows that LCA provides objective data flows regarding different waste management strategies and quantifies the environmental impact of each alternative. LCA allows for the improvement of the existing waste management system by comparing alternative systems based on qualified data.

This study only evaluated the environmental aspect of the waste management alternatives. Additional evaluations that consider the life cycle perspective should be conducted to determine the social and economic effects of alternative strategies to fully assess the sustainability of decisions related to solid waste management.

4. Conclusions

Currently, MSW in the city of Riyadh, Saudi Arabia, is mainly landfilled. In 2016, the city strengthened the Comprehensive Waste Management Strategy in order to face the rising levels of waste generated. In this study, we analyzed the Strategy proposals from the perspective of life cycle assessment, evaluating the environmental impact of different stages, defined as S0 (current situation), S1 (scenario to be fulfilled in 2023), and S2 (scenario to be implemented in 2035).

S1 and S2 include waste incineration, material recycling, and biowaste treatment instead of landfilling, treatments that are energy- and resource-intensive. Even though S1 and S2 have higher environmental impacts than S0 (landfill) due to the treatment itself, the benefits beyond the system have to be considered.

The waste recycling and waste-to-energy MSW treatments are proven to be essential to solve the waste disposal problems, but also to reduce the GHG emissions generated by MSW management, generate renewable energy, and recover the value of materials, which are key values of the circular economy. Even still, the success of the alternative management systems is dependent on households' views towards waste separation, the collection schemes implemented by the municipality, and how the cost is attributed.

Saudi Arabia has set environmental goals in SV2030 that state that 2% of electricity has to be generated from WtE. In this study, the electricity generated by MSW in 2023 when S1 is completed and in 2035–2045 when S2 is implemented was evaluated and compared with the electricity demanded by the residential sector. Even though the S2 strategy allows for a higher reduction in the net impact of the MSW generated in Riyadh, S1 is the scenario that better serves to fulfill the SV2030 goals. Taking into consideration the SV2030 goal of producing 2% of electricity from WtE, it is more likely to be achieved under the S1 scenario, with a share of 80% WtE management.

In 2023, with S1 fully implemented, WtE from MSW could cover 3.17% of the electricity demanded by households, which could represent 1.51% of all sectors' demand. Therefore, all sectors have to contribute to generating electricity from waste, not just the MSW generated by households, to hit the target of 2% of total electricity from WtE.

Moreover, as the population is expected to increase significantly in the coming years, additional measures to reduce the electricity demand have to be taken in all sectors, but special attention has to be put into the residential sector, responsible for nearly half of the Saudi Arabian electricity demand.

In this study, the MSW management was evaluated assuming that the population and, in consequence, the waste generated by the residential sector will increase significantly. However, one of the first measures to be focused on that we did not assess in this study is the need to separate the population growth from the waste generation and resource consumption (like electricity). Therefore, the efforts have to primarily be made at the social level.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14095093/s1, Table S1: Contribution on the environmental impact of each MSW fraction and contribution to the MSW; Table S2: The environmental impact for each scenario and impact category of treating 1 ton of MSW collected (FU), the avoided impact, and the net impact considering system expansion.

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Nomenclature

LCA	life cycle assessment
MRF	material recovery facilities
MSWM	municipal solid waste management
WtE	waste to energy
MSW	municipal solid waste
GHG	greenhouse gases
SV2030	Saudi Vision 2030

K.A.CARE	King Abdullah City for Atomic and Renewable Energy
MAP	mean annual precipitation
AD	anaerobic digestion
WEEE	waste electrical and electronic equipment
RDF	refused derived fuel
SRF	solid recovered fuel
FU	functional unit
RnSE	renewable and sustainable energy
LCIA	life cycle impact assessment

References

1. Arena, U.; Mastellone, M.L.; Perugini, F. The environmental performance of alternative solid waste management options: A life cycle assessment study. *Chem. Eng. J.* **2003**, *96*, 207–222. [CrossRef]
2. Maalouf, A.; El-Fadel, M. Life cycle assessment for solid waste management in Lebanon: Economic implications of carbon credit. *Waste Manag. Res.* **2019**, *37*, 14–26. [CrossRef] [PubMed]
3. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.P.; Suh, S.; Weidema, B.P.; Pennington, D.W. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environ. Int.* **2004**, *30*, 701–720. [CrossRef] [PubMed]
4. Winkler, J.; Bilitewski, B. Comparative evaluation of life cycle assessment models for solid waste management. *Waste Manag.* **2007**, *27*, 1021–1031. [CrossRef]
5. Güereca, L.P.; Gassó, S.; Baldasano, J.M.; Jiménez-Guerrero, P. Life cycle assessment of two biowaste management systems for Barcelona, Spain. *Resour. Conserv. Recycl.* **2006**, *49*, 32–48. [CrossRef]
6. Abeliotis, K. Life Cycle Assessment in Municipal Solid Waste Management. In *Integrated Waste Management*; Kumar, S., Ed.; IntechOpen: Rijeka, Croatia, 2011; Volume I, Available online: https://www.intechopen.com/chapters/17450 (accessed on 27 February 2022). [CrossRef]
7. Mendes, M.R.; Aramaki, T.; Hanaki, K. Comparison of the environmental impact of incineration and landfilling in São Paulo City as determined by LCA. *Resour. Conserv. Recycl.* **2004**, *41*, 47–63. [CrossRef]
8. 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]
9. Oyoo, R.; Leemans, R.; Mol, A.P. Comparison of environmental performance for different waste management scenarios in East Africa: The case of Kampala City, Uganda. *Habitat Int.* **2014**, *44*, 349–357. [CrossRef]
10. Dong, J.; Chi, Y.; Zou, D.; Fu, C.; Huang, Q.; Ni, M. Comparison of municipal solid waste treatment technologies from a life cycle perspective in China. *Waste Manag. Res.* **2014**, *32*, 13–23. [CrossRef]
11. Skrzypkowski, K.; Korzeniowski, W.; Młynarska, P. Binding capability of ashes and dusts from municipal solid waste incineration with salt brine and geotechnical parameters of the cemented samples. *Arch. Min. Sci.* **2018**, *63*, 903–918. [CrossRef]
12. Korzeniowski, W.; Poborska-Młynarska, K.; Skrzypkowsk, K. The idea of the recovery of municipal solid waste incineration(MSWI) residues in Kłodawa salt mine S.A. By filling the excavations with self-solidifying mixtures. *Arch. Min. Sci.* **2018**, *63*, 553–565. [CrossRef]
13. Mumbach, G.D.; Alves, J.L.; Da Silva, J.C.; De Sena, R.F.; Marangoni, C.; Machado, R.A.; Bolzan, A. Thermal investigation of plastic solid waste pyrolysis via the deconvolution technique using the asymmetric double sigmoidal function: Determination of the kinetic triplet, thermodynamic parameters, thermal lifetime and pyrolytic oil composition for clean energy recovery. *Energy Convers. Manag.* **2019**, *200*, 112031.
14. da Silva Filho, V.F.; Batistella, L.; Alves, J.L.; da Silva, J.C.; Althoff, C.A.; Moreira, R.D.; José, H.J. Evaluation of gaseous emissions from thermal conversion of a mixture of solid municipal waste and wood chips in a pilot-scale heat generator. *Renew. Energy* **2019**, *141*, 402–410. [CrossRef]
15. Hadidi, L.A.; Ghaithan, A.; Mohammed, A.; Al-Ofi, K. Deploying municipal solid waste management 3R-WTE framework in Saudi Arabia: Challenges and future. *Sustainability* **2020**, *12*, 5711. [CrossRef]
16. AlHumid, H.A.; Haider, H.; Alsaleem, S.S.; Shafiquzamman, M.; Sadiq, R. Performance indicators for municipal solid waste management systems in Saudi Arabia: Selection and ranking using fuzzy AHP and PROMETHEE II. *Arab. J. Geosci.* **2019**, *12*, 491. [CrossRef]
17. Zafar, S. Solid Waste Management in Saudi Arabia. EcoMena Articles. 2013. Available online: http://www.ecomena.org/solidwaste-management-in-saudi-arabia/ (accessed on 16 January 2022).
18. Mallick, J. Municipal solid waste landfill site selection based on fuzzy-AHP and geoinformation techniques in Asir Region Saudi Arabia. *Sustainability* **2021**, *13*, 1538. [CrossRef]
19. 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]
20. Garba, S.B. Managing urban growth and development in the Riyadh metropolitan area, Saudi Arabia. *Habitat Int.* **2004**, *28*, 593–608. [CrossRef]

21. King Abdullah Petroleum Studies and Research. Available online: https://datasource.kapsarc.org/explore/dataset/saudi-arabia-population-by-administrative-region-nationality-and-sex/information/?disjunctive.administrative_region&disjunctive.gender (accessed on 15 February 2022).
22. Bashir, B.; Alsalman, A.; Othman, A.A.; Obaid, A.K.; Bashir, H. New Approach to Selecting Civil Defense Centers in Al-Riyadh City (KSA) Based on Multi-Criteria Decision Analysis and GIS. *Land* **2021**, *10*, 1108. [CrossRef]
23. Saudi Gazette. Riyadh Unveils New Waste Management and Recycling Plan. 2019. Available online: https://saudigazette.com.sa/article/571891 (accessed on 5 January 2022).
24. Riyadh Environment. Comprehensive Waste Management Strategy for ArRiyadh City. Available online: https://www.riyadhenv.gov.sa/wp-content/uploads/2016/12/Comprehensive-Waste-Management-Strategy-for-ArRiyadh-City.pdf (accessed on 15 January 2022).
25. 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]
26. Den Boer, J.; Den Boer, E.; Jager, J. LCA-IWM: A decision support tool for sustainability assessment of waste management systems. *Waste Manag.* **2007**, *27*, 1032–1045. [CrossRef] [PubMed]
27. *ISO-14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
28. *ISO-14044*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
29. Doka, G.; Hischier, R. Waste Treatment and Assessment of Long-Term Emissions (8pp). *Int. J. Life Cycle Assess.* **2005**, *10*, 77–84. [CrossRef]
30. Gala, A.B.; Raugei, M.; Fullana-i-Palmer, P. Introducing a new method for calculating the environmental credits of end-of-life material recovery in attributional LCA. *Int. J. Life Cycle Assess.* **2015**, *20*, 645–654. [CrossRef]
31. Laurent, A.; Clavreul, J.; Bernstad, A.; Bakas, I.; Niero, M.; Gentil, E.; Christensen, T.H.; Hauschild, M.Z. Review of LCA studies of solid waste management systems—Part II: Methodological guidance for a better practice. *Waste Manag.* **2014**, *34*, 589–606. [CrossRef]
32. Khan, M.U. Saudi Arabia's vision 2030. *Def. J.* **2016**, *19*, 36.
33. Zell, E.; Gasim, S.; Wilcox, S.; Katamoura, S.; Stoffel, T.; Shibli, H.; Engel-Cox, J.; Al Subie, M. Assessment of solar radiation resources in Saudi Arabia. *Sol. Energy* **2015**, *119*, 422–438. [CrossRef]
34. Doka, G. *A Model for Waste-Specific and Climate-Specific Life Cycle Inventories of Open Dumps and Unsanitary Landfilling of Waste*; Doka Life Cycle Assessments: Zurich, Switzerland, 2017; Available online: http://www.doka.ch/publications.htm (accessed on 15 January 2022).
35. Doka, G. *Inventory Parameters for Regionalised Mixes of Municipal Waste Disposal in Ecoinvent v3.5*; Technical Report; Doka Life Cycle Assessments: Zurich, Switzerland, 2018.
36. Blengini, G.A.; Fantoni, M.; Busto, M.; Genon, G.; Zanetti, M.C. Participatory approach, acceptability and transparency of waste management LCAs: Case studies of Torino and Cuneo. *Waste Manag.* **2012**, *32*, 1712–1721. [CrossRef]
37. Schmidt, A. *Gaining Benefits from Discarded Textiles: LCA of Different Treatment Pathways*; Nordic Council of Ministers: Copenhagen, Denmark, 2016.
38. Gaines, L.L.; Mintz, M.M. *Energy Implications of Glass-Container Recycling*; Argonne National Lab.: Lemont, IL, USA; National Renewable Energy Lab.: Golden, CO, USA, 1994.
39. 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.
40. Luo, Q.; Yao, Z.; Qi, W.; Sun, J.; Gedanken, A.; Chen, X.; Sun, Y.; Liu, J.; Xu, S.; Wu, W. A comprehensive study on the combustion kinetic modeling of typical electronic plastic waste—Television set (TV) plastic shell. *J. Air Waste Manag. Assoc.* **2021**, *71*, 701–710. [CrossRef]
41. Wäger, P.A.; Hischier, 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]
42. Huijbregts, M.A.; Steinmann, Z.J.; Elshout, P.M.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
43. Vitale, G.; Mosna, D.; Bottani, E.; Montanari, R.; Vignali, G. Environmental impact of a new industrial process for the recovery and valorisation of packaging materials derived from packaged food waste. *Sustain. Prod. Consum.* **2018**, *14*, 105–121. [CrossRef]
44. Huijbregts, M.A.; Steinmann, Z.J.; Elshout, P.M.; Stam, G.; Verones, F.; Vieira, M.; Hollander, A.; Zijp, M.; Van Zelm, R. Available online: https://pre-sustainability.com/legacy/download/Report_ReCiPe_2017.pdf (accessed on 25 February 2022).
45. PRé. SimaPro. Available online: http://www.pre-sustainability.com/simapro (accessed on 25 February 2022).
46. Al-Awsat, A. Middle-East Arab News Business. Available online: https://english.aawsat.com/home/article/2782651/riyadh-strategy-boost-population-growth (accessed on 10 January 2022).
47. General Authority for Statistics, Saudi Arabia. Available online: https://www.stats.gov.sa/en/1007-0 (accessed on 2 January 2022).
48. Saudi Arabian Monetary Authority (SAMA). *Annual Statistics 2019*; Saudi Central Bank: Riyadh, Saudi Arabia, 2020.