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Moving from Linear to Circular Economy in Saudi Arabia: Life-Cycle Assessment on Plastic Waste Management

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Abstract: The discovery of plastic caused a true transformation in human lives and it is used in many essential applications. Despite its significance, humanity struggles to control plastic waste and stop its infiltration into the natural environment. This study aims to review the existing waste management system in Saudi Arabia and evaluate environmental impacts of different plastic waste management scenarios by conducting a life-cycle assessment (LCA). This study covered five scenarios: landfill, incineration with energy recovery, mechanical recycling with incineration of residuals, pyrolysis with incineration of residuals, and combined mechanical recycling and pyrolysis with incineration of residuals. For all scenarios in this study, the CML-IA Baseline method was used, utilizing OpenLCA software. Sources of data for this study were obtained from the Ecoinvent 3.9.1 database and from published peer-reviewed reports. The LCA study revealed that the combined mechanical recycling and pyrolysis with incineration of residuals scenario has the lowest environmental impact. Additionally, the combined scenario can accept a broader range of plastic waste, which improves the overall waste management system towards shifting to circular economy. Therefore, to meet the various recycling requirements, it is recommended to establish a portfolio of plastic waste management techniques in Saudi Arabia to produce high-quality recycled products. It is also recommended to utilize renewable energy for electricity generation in Saudi Arabia, since it was shown in this study that it has a significant positive environmental impact across all impact categories.

Keywords: life-cycle assessment; plastic waste management; circular economy; sustainability

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1. Introduction

Plastics play a significant role in our daily life and have influenced the development of the modern economy. Plastics are used in various applications that we utilize in our daily lives and have become a necessity that cannot be replaced. Examples of these applications are food, general-purpose packaging, building and construction, fabrics, footwear, automobiles, electrical and electronic equipment, and machinery. Vast consumption of plastics caused by a wide range of applications and inexpensive prices has led to an enormous buildup of plastic waste. An estimate of global plastic production in 2020 was 367 million tons, which has risen from 1.5 million tons in 1950 [1]. An estimate of the total cumulative plastic that was produced until 2019 is around 9.5 billion tons of plastic [2]. Vast consumption of plastics has led to significant plastic waste issues globally. Therefore, many countries around the world have banned single-use plastic or limited its use [3].

The linear model of obtaining material from the natural environment, processing that material, using it, and then sending the material to waste has many drawbacks, which requires a more robust circular economy approach. The linear model is quite effective at producing material wealth, but in recent years it has shown limitations owing to resource depletion and negative environmental effects. Therefore, the model of make, use, then dispose must be changed for our planet's sustainability [4]. The circular plastic economy is gaining traction as a reaction to these difficulties, with the objective of reducing, reusing,

and recycling all plastic. Preston defined the idea of a circular economy as follows: "open production systems in which resources are extracted, used to make products and become waste after the product is consumed—should be replaced by systems that reuse and recycle resources and conserve energy" [5].

The production of plastic waste and the process of waste management has an impact on air, water, and soil. This waste can impact the environment in three ways: leakage into nature, especially oceans, where around 8 to 13 million tons of plastics are released into the oceans annually [6]; the release of greenhouse gases as a result of production and post-use incineration; and the health and environmental effects of microplastics and additives [7].

Plastic waste is increasing year after year due to constant growth in population and economic development globally, which can lead to challenging environmental and health issues [8]. This growth of waste generation necessitates the development of a system that can properly extract the most value out of the waste stream and safely dispose of it. According to Geyer et al., only 21% of the 8300 million tons of plastic generated between 1950 and 2015 were recycled or incinerated; the remaining 6300 million tons (or more) were disposed of or found their way into the natural environment [9]. A new strategy in Saudi Arabia was proposed to be implemented by 2035, where 42% of waste will be recycled, 35% will be composted, 19% will be incinerated for energy recovery, and 4% will be managed by other means [10]. The new strategy will significantly advance achieving the kingdom's priority of a cutting-edge, low-carbon, and energy-efficient economy. It will significantly advance achieving the sustainable development objectives. Studies are urgently needed to understand the factors that lead to plastic leakage, according to many stakeholders. Understanding the costs and benefits of plastic also requires research into life-cycle assessments (LCAs). LCA is utilized predominantly to compare environmental impacts of different alternatives [3]. Therefore, to make judgments that identify the conflict between sustainability aims and circularity objectives, policymakers should be aware of and understand the importance of this topic. This aim of this research is to assess the environmental impact of plastic production by carrying out life-cycle assessment to calculate greenhouse gas emissions per kg of plastic, followed by applying different waste management strategies to reduce greenhouse emissions and quantify the effect through LCA. This research will compare, contrast, and then recommend plastic waste management approaches based on environmental impacts.

1.1. Waste Management

Waste management can be defined as the process of collecting, transporting, treating, recycling, and safely disposing of waste [11]. The solid waste management hierarchy shown in Figure 1 prioritizes these methods from the most preferred to the least preferred. The European Commission defines the waste hierarchy as "The waste hierarchy generally lays down a priority order of what constitutes the best overall environmental option in waste legislation and policy, while departing from such hierarchy may be necessary for specific waste streams when justified for reasons of, inter alia, technical feasibility, economic viability and environmental protection" [12,13]. The four most preferred method in the waste hierarchy are waste prevention from the source, waste minimization, waste reduction, and then recycling. These four methods are well known and are considered the key pillars of circular economy concepts [14–16]. The bottom two methods, which are least favored, are energy recovery, which is mostly carried out through incineration; and waste disposal in dumping sites, which are also called landfills. Countries employ different combinations of the formerly mentioned waste management systems, and the choice of waste management systems in these countries is subject to multiple factors. The most crucial factors are countries' waste management policies that govern uncontrolled waste disposal, and the level of education and awareness of the public towards reducing, reusing, and recycling. Figure 1 [17] shows the direction of the preferred waste management hierarchy. The European Commission advice that the choice of the waste management

option should be determined through a decision on the best environmental option was concluded from results obtained from LCAs [12].

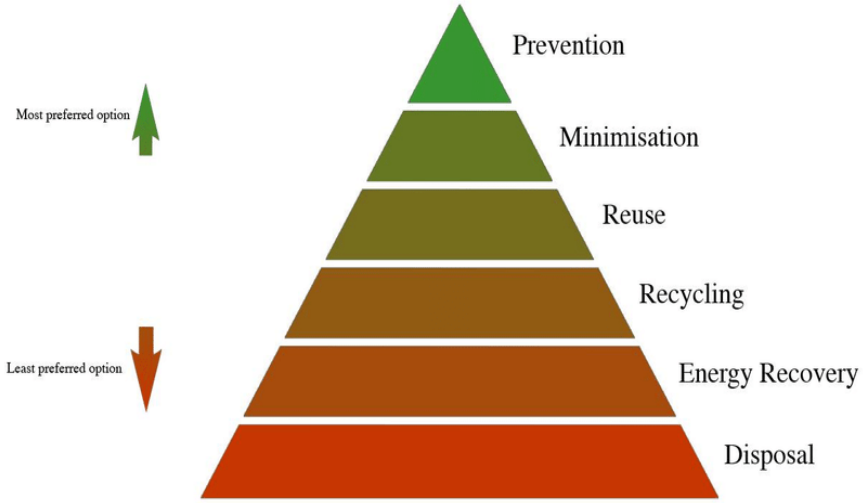


Figure 1. Waste management hierarchy [17].

Waste comes from various sources which are typically classified under the following categories according to the United Nations Global Waste Management Outlook [18]:

- Municipal Solid Waste (MSW): This is a waste stream that is generated from households that includes paper, plastic, food, and others.
- Industrial Waste: This is a waste stream that is generated from manufacturing processes which include chemical and hazardous materials.
- Commercial Waste: Source of this waste is from businesses, organizations, and institutions.
- Construction and Demolition (C&D) Waste: This waste is generated from activities related to building and demolition.
- Energy production waste: This waste is generated from the production of energy from fossil fuels, nuclear power, and renewable energy.
- Water supply, sewage treatment, waste management, and land remediation waste: This is a waste stream generated from provisions of clean water, sewage sludge treatment, solid waste treatment from waste management plants, and contaminated solids from land remediation initiatives.

The United Nations gathered data for the Organization for Economic Cooperation and Development (OECD) countries' waste stream composition, which is represented in Figure 2.

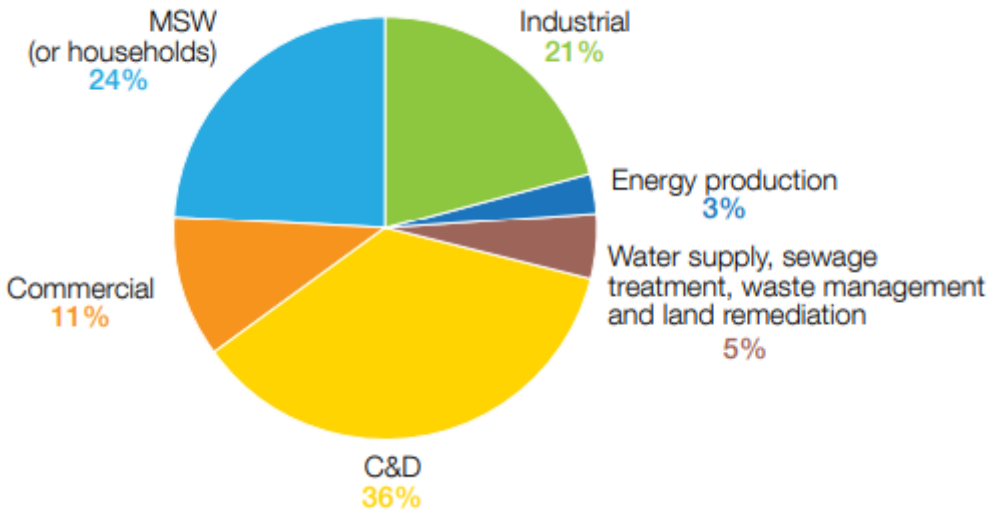


Figure 2. Waste stream relative split in OECD countries [18].

As depicted in Figure 2, the three major contributors of waste are construction and demolition, accounting for 36% of total waste; industrial and commercial waste, accounting for 32% of total waste; and MSW, accounting for 24% of total waste in OECD countries.

As of 2020, global MSW generation was estimated to be 2.24 billion tons. The forecasted amount of MSW generation by 2050 is expected to reach 3.88 billion, as shown in Figure 3 [19]. The estimates shown in Figure 3 were based on assumptions related to GDP per capita growth rate and population growth, which are considered to be critical factors influencing waste generation.

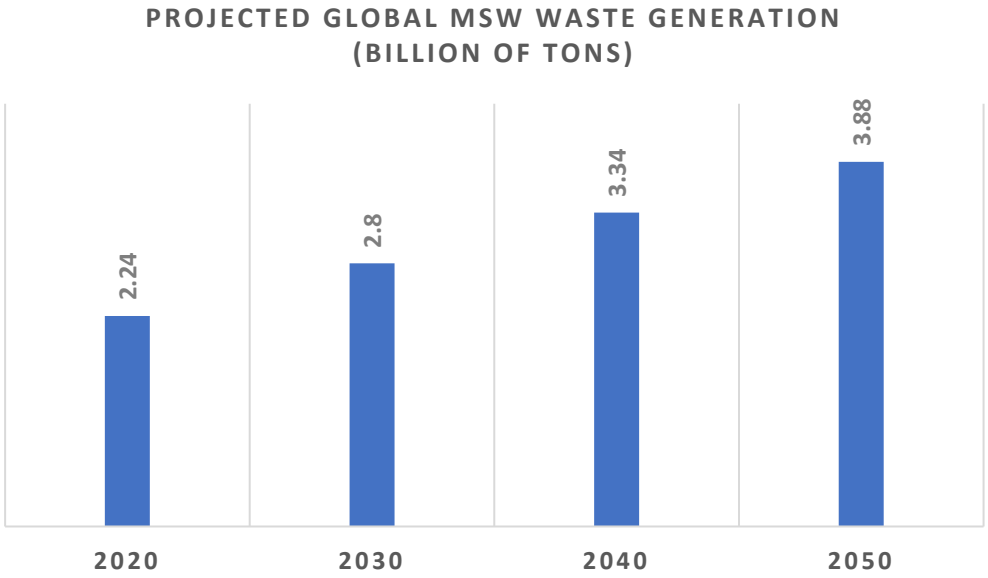


Figure 3. Projected global MSW waste generation [19].

MSW streams are composed of different materials with varying percentages of organic waste, glass, metal, plastic, paper, green waste, wood, rubber, leather, and other materials. The composition of waste streams is different from country to country, which is governed by many factors. The most influential factor is the socio-economic situation of the country [20]. Low-to-medium income countries tend to have higher organic waste composition. On the other hand, high-income countries tend to have high metal, glass, plastic, and paper composition [21]. The World Bank [22] has a comprehensive database for waste management that covers almost all countries globally and more than three hundred cities. Composition of waste per region is shown in Table 1.

Table 1. MSW waste composition in percentage by region [22].

	Organic Waste	Glass	Metal	Others	Plastic	Paper	Green Waste	Wood	Rubber and Leather
Sub-Saharan Africa	42.3	2.2	2.6	27.7	7.7	7.4	8.9	1.1	0.2
East Asia and Pacific	32.9	3.5	5.7	13.0	12.0	13.1	10.3	7.3	2.2
Europe and Central Asia	30.3	5.7	3.1	20.5	9.3	16.1	9.4	3.6	1.9
Latin America and Caribbean	38.2	4.7	3.6	10.9	11.3	13.9	11.0	4.2	2.2
Middle East and North Africa	51.4	3.0	3.3	9.3	11.8	12.7	1.9	2.0	4.7
North America	15.6	5.4	7.8	10.4	8.1	28.6	11.1	5.2	7.9
South Asia	43.6	2.9	1.6	8.1	7.4	9.1	22.8	3.4	1.1
Average	36.3	3.9	4.0	14.3	9.6	14.4	10.8	3.8	2.9

As shown in Table 1, organic waste has the highest percentage in most regions, with the highest percentage in the Middle East and North Africa, accounting for 51.4% of the MSW. Plastic waste composition is high in all regions, peaking at 12% in the East Asia and Pacific region. This shows a great need for proper plastic waste management practices globally.

There are several ways to deal with waste in general and plastic waste in particular. Each country has a distinct split of waste management. The OECD [23] has reported data regarding waste management techniques for all participating countries. Waste management techniques were categorized as recycling, composting, incineration with energy recovery, incineration without energy recovery, landfill, other disposal, and other recovery. Figure 4 shows percentage statistics gathered for Europe, America, Asia Oceania, and total OECD for the year of 2020 [23].

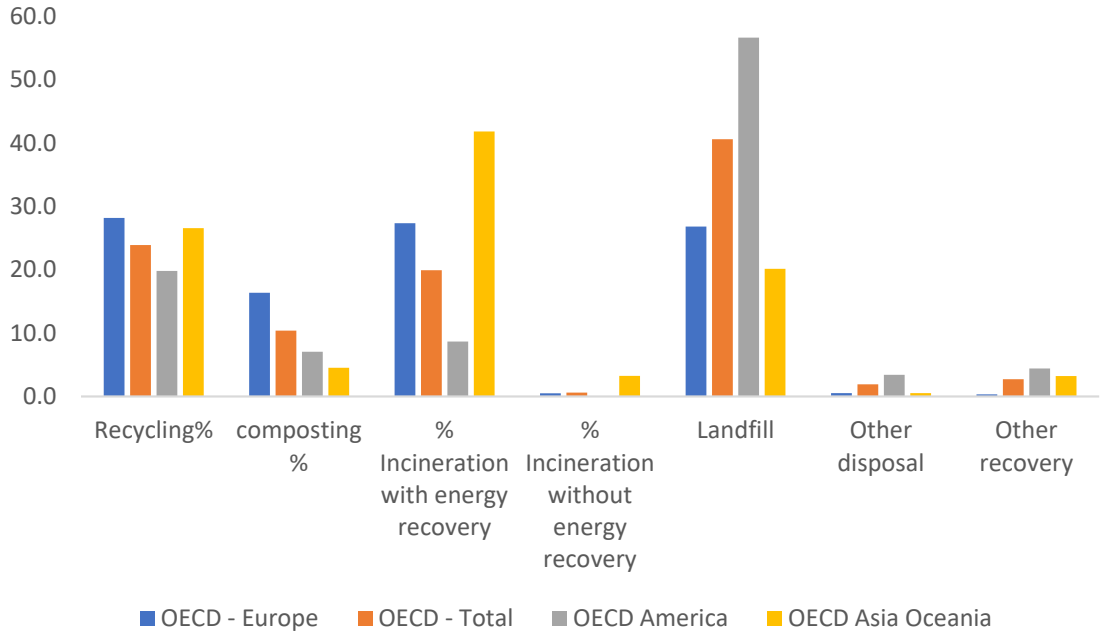


Figure 4. Waste management techniques split between OECD countries in 2020 [23].

Landfills still account for a substantial portion of waste management techniques globally, averaging around 40% for all OECD countries. Recycling percentage across all regions is quite similar, ranging from 20% to 30%. In Europe, composting is more widely used than in the other regions, with a percentage of 16%. Incineration with energy recovery has wide variations across regions, being the highest in Asia Oceania with a percentage exceeding 40% and the lowest in America with a percentage of around 10%. Incineration without energy recovery is quite low in all regions when compared to other techniques. The highest percentage of landfill in OECD countries is in America, which is around 57%. On the other hand, the Asia Oceania region has the lowest percentage of landfill in OECD countries of around 20%.

1.2. Waste Management in Saudi Arabia

Proper handling and management of solid waste is essential for all countries around the world. In Riyadh, most of the waste is produced from construction and demolition sites, accounting for around 78% of total waste generated. This is followed by MSW and industrial waste, which are both similar in quantity, each accounting for around 12% and 9% of total waste, respectively. Finally, medical and sewage sludge wastes are small, accounting for <1% of total waste. Waste generation per type in Riyadh is depicted in Figure 5 [24]. The extremely high percentage of construction and demolition waste is driven by economic and population growth in Saudi Arabia, resulting in increased demands for housing and infrastructure [25].

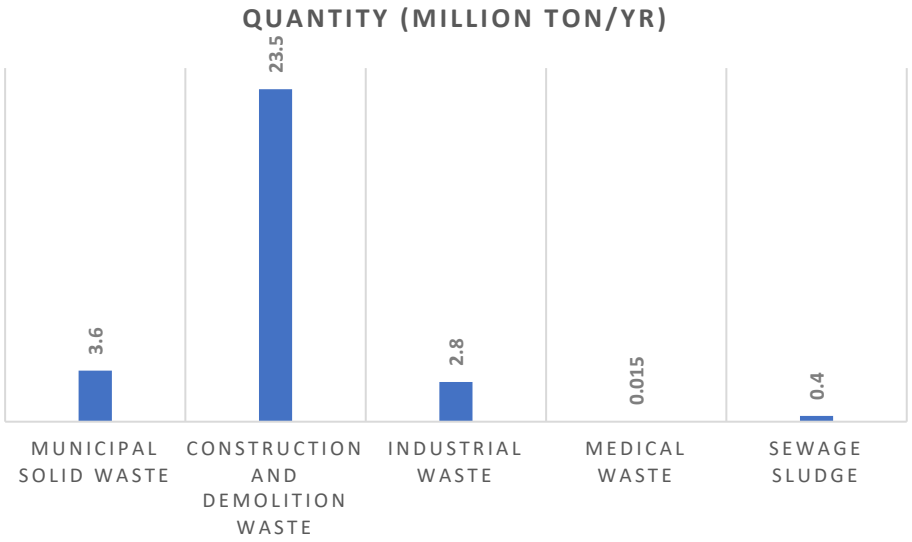


Figure 5. Waste generation per type in Riyadh, Saudi Arabia [25].

Waste generation per capita refers to the amount of waste generated by each person in a population. The main factor affecting waste generation per capita is the income level of the population, defined by the Gross Domestic Product (GDP) metric. Studies have shown that a higher-income population, on average, generates higher waste per capita compared to a lower-income population [26]. This relationship between GDP and waste generation per capita can be explained by the fact that higher GDP leads to higher consumer activities and business growth [27]. Other factors affecting MSW generation per capita are urbanization, literacy, level of public awareness, and availability of sanitary services [28]. Data for waste generation per capita were reported by the World Bank global data set. Figure 6 shows the MSW generated per capita of ten cities globally, including Riyadh and Jeddah [22].

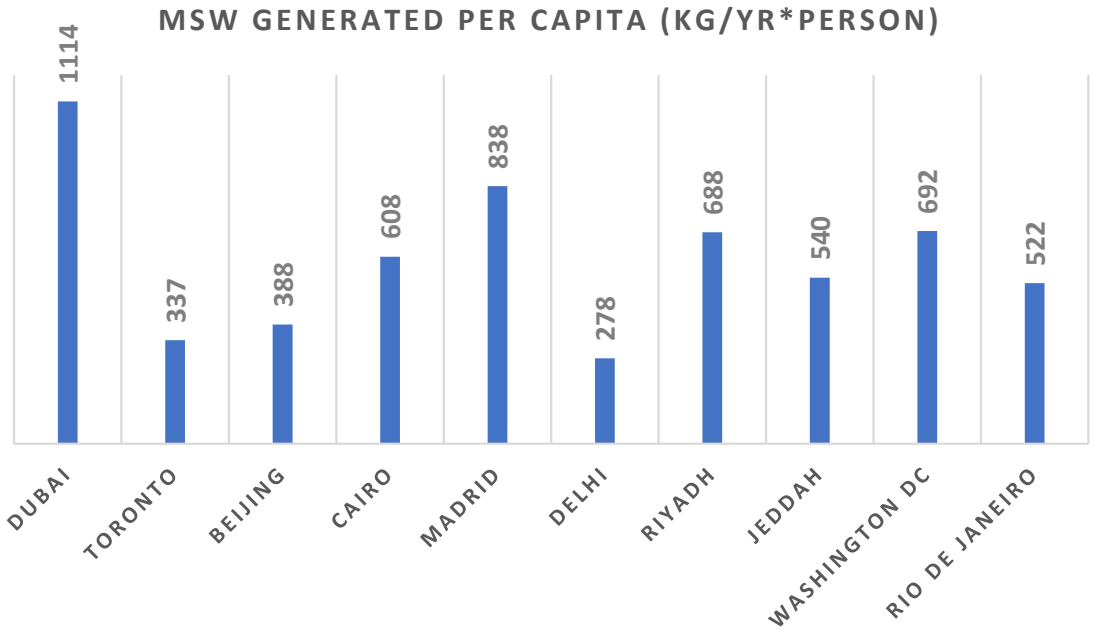


Figure 6. Waste generation per capita of ten cities [22].

The quantity of MSW generated in Saudi Arabia is shown in Figure 7. The general trend is that MSW generation is increasing every year [29].

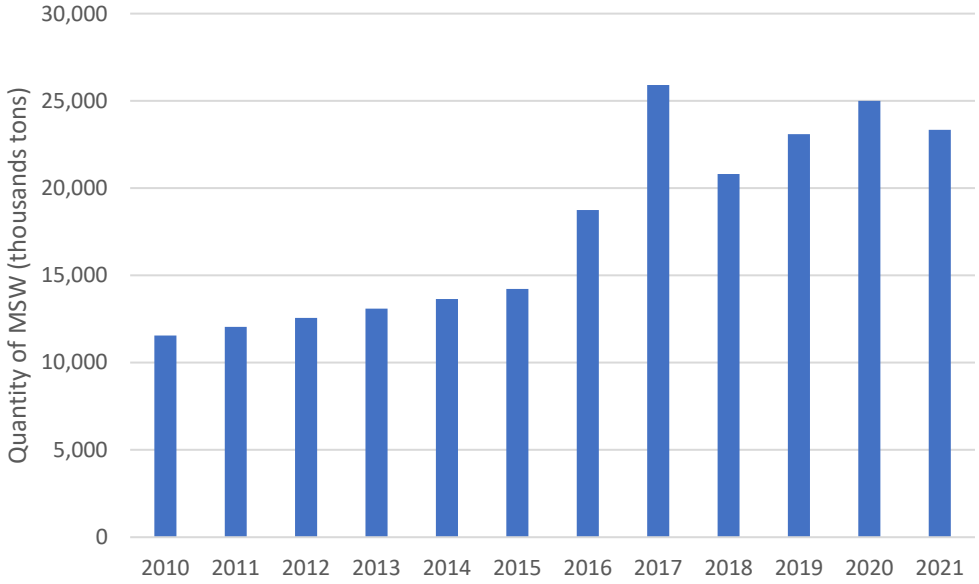


Figure 7. Quantity of MSW in Saudi Arabia [29].

The composition of MSW in Riyadh, Saudi Arabia was obtained from the World Bank database and shown in Figure 8 [22]. More than 50% of MSW in Riyadh is caused by organic waste, which is much higher than average organic waste in all regions globally, as shown in Table 1 [24]. This large amount organic waste can be attributed to many factors, including high GDP per capita causing high public spending, local traditions that encourage preparation of substantial portions of foods during celebrations, and lack of awareness of the negative financial and environmental impacts of food waste [30].

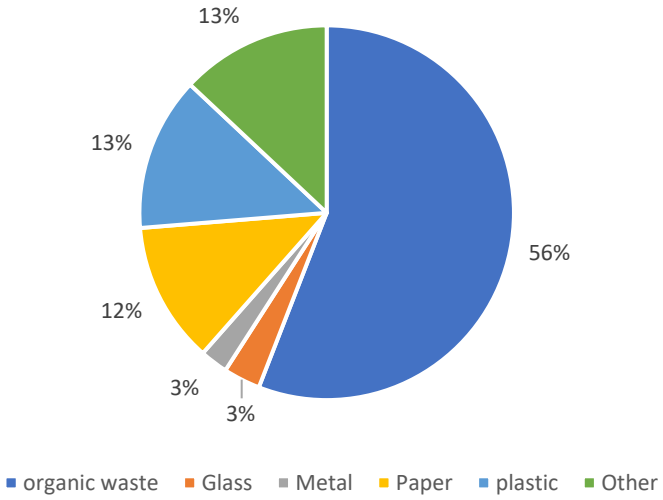


Figure 8. MSW percentage composition in Riyadh, Saudi Arabia [22].

Data for waste management techniques was reported by the World Bank global data set. As can be seen in Figure 9, disposal in controlled landfills is considered the primary waste management technique in Saudi Arabia, accounting for 85% of the total waste. Recycling accounts for the remaining amount, which is 15%. The majority of waste collection for recycling in Saudi Arabia is conducted by an informal sector which gathers and separates paper, plastic, and metallic material waste from MSW [31]. The new strategy in Saudi Arabia will significantly advance achieving the kingdom's priority of a cutting-edge, low-carbon, and energy-efficient economy. This will significantly advance achieving the sustainable development objectives.

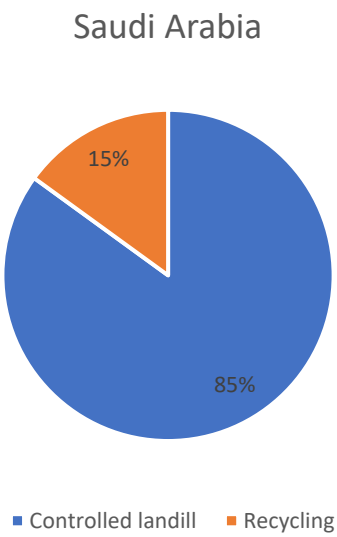


Figure 9. Waste management techniques split in Saudi Arabia [22].

2. Literature Review

As per the study conducted by Johnson et al., for the true implementation of a circular economy, the whole value chain must be examined and circular economy concepts applied to each stage. According to Johnson et al. [32] a circular economy transition should start from the material design stage. The focus of this stage is the product to be designed for ease of recycling or downgauging so that less material is used in the final application [32]. The second phase is the production of plastic, including the manufacturing of plastic pellets and the processing of plastic to its final application. The process of making plastic could use alternative feedstocks that are based on renewable sources. Chen et al. [33], in 2020, reviewed the current state of the art, covering the main commercial renewable plastics and the new generation of renewable plastics [33]. Plastic converters could mix virgin plastic with recycled plastic of different proportions. However, the main challenges of this approach reported in the literature include the deterioration of final product properties, contaminations, and toxicity [34]. The third phase is consumer usage of plastics. This stage focuses on providing awareness to the public on how to best handle and dispose of plastic and limit the use of single-use plastic towards shifting to more durable applications.

Raising public awareness is a critical step in increasing the percentage of plastic and other material recycling rates through plastic separation from the point of generation. In research conducted to evaluate recycling awareness in Jordan, researchers concluded that due to the lack of appropriate disposal programs across the country, most respondents do not know enough about where and how to recycle. Loizia et al. [35], 2021, talked about the effect of pandemic on the environment and how it affects public health. It also appears that awareness initiatives now available in Jordan are insufficient and need to be more productive [36]. The final stage is the end of life of plastics, which includes sorting, recycling, and waste management technologies. One of the ways to increase the effectiveness of waste collection is through the integration of AI artificial intelligence) techniques into the existing system. Some studies have attempted to reduce the route length of the collecting trucks by digitizing the solid waste bin maps [37]. Karadimas et al. [38], 2016, presented an interesting concept and methodology to utilize RFID (radio frequency identification) technology. Ultrasonic sensors are the detecting elements used in this use case, and they generate ranging information that is converted to fill-level estimates [38]. In a related study, waste containers with ultrasound sensors were used to collect waste more effectively. These devices measured three factors inside a waste container: the volume of the container, which determines its total capacity; the length from its bottom to the top level; and the length of the empty portion of the container. These data were sent to a database, which used software to plan the waste collection journeys and notify the

collection vehicles [39]. Sidhu et al. [40], proposed a simple solution for smart trash bins equipped with weight scales that feed data into a modeling software that forecasts the quantity of plastic waste in each trash bin. The prediction model's outcomes are fed into a trip planning algorithm, which generates optimal routes for waste collection trucks to increase the amount of waste collected in the least amount of time [40]. There is also a commercial waste collection device called Bine. Internet of things and data mining technologies are used in the suggested waste management container to effectively manage municipal waste. This invention covers features like waste identification and waste sorting by types, such as glass, metal, paper, and plastic. In addition, it includes compression of the trash to decrease its size prior to pick up, regulation of the container's level, and wireless technology with a centralized processing device. This system provides real-time waste management tracking and logistics optimization for waste collection [41].

LCA offers a complete analysis of the environmental impacts of a product. Effective LCA assesses a process from acquiring raw materials through manufacturing to the consumption and eventual disposal of a product. When properly constructed, LCAs can give stakeholders insights on ways to improve waste management systems to maintain plastics in the circular economy and minimize their environmental impacts [42]. In research conducted by Rajendran, the author compared mechanical recycling for plastics against incineration with energy recovery. The method used for comparison was based on life-cycle assessment. Both methods have shown positive environmental benefits. However, the mechanical recycling benefits exceeded the second option due to the fact that it was assumed that recycled polymers will replace virgin polymers in a 1:1 ratio. The replacement of virgin polymers with recycled polymers is beneficial due to avoiding the burden from using 100% virgin polymer [43]. Anna Ruban [44] researched the most sustainable type of plastic bags by conducting LCA. The research revealed that biodegradable vest bags are the most sustainable option and will impart the least burden to the environment [44]. Koo Hai Choon [45] conducted research on a plastic life-cycle assessment. He provided several recommendations to manage plastic's impact on the environment. First, a greener plastic production industry is needed, in which governments need to impose strict regulations on emissions. Secondly, more research is needed to understand the negative impact of plastic additives leaching out on human health. Thirdly, a reduction of plastic waste is needed by shifting the cultural mindset of disposing of plastic and making recycling a habit for the public. Fourthly, the government can start implementing taxation and other limiting policies to reduce plastic waste. Aldhafeeri and Alhazmi in 2022, and Alhazmi et al. in 2022, raised the issue of the importance of public awareness in Saudi Arabia regarding waste management and its importance to the economy [15,16]. Finally, using more recycling-friendly products, such as polypropylene, is recommended to reduce hard-to-recycle products [45].

3. Methods

Calculations of environmental impacts in this report will be conducted through LCA. LCAs offer a complete picture of the environmental impacts of a product. LCA is a tool used to evaluate all environmental aspects of the process, such as resource depletion, acidification potentials, GHG emissions, and waste that take place during the whole product life cycle. LCA calculations are a critical element of the transition to circular economy. Effective LCA assesses a process from acquiring raw materials through manufacturing to the consumption and eventual disposal of a product, which is also called "cradle to grave". Most products undergo the following phases [46]:

1. Raw material extraction;
2. Manufacturing;
3. Transportation;
4. Usage;
5. Waste disposal.

LCA can model the entire life cycle of a product, or part of it, depending on the scope of the study and the system boundaries. When conducting LCAs, there are different approaches to be followed depending on the research objectives [47] as shown in Figure 10:

1. Gate to gate: this considers environmental impacts of only one stage of the product life cycle.
2. Cradle to gate: takes into account environmental impacts of the first two stages: raw material extraction and manufacturing.
3. Cradle to grave: takes into account environmental impacts of all stages of product life cycle from raw material extraction to waste disposal.
4. Cradle to cradle: similar to cradle to grave, but includes product recycling into a new life cycle.

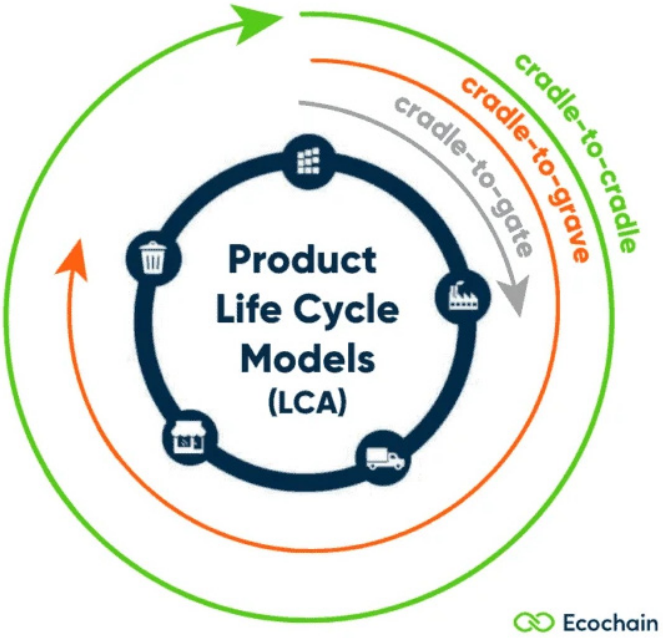


Figure 10. LCA approaches in product life cycle [47].

Figure 10 depicts how LCA can be applied throughout a product's life cycle.

The most recent ISO 14040 standards outline and regulate the procedures for conducting a proper LCA [48]. LCA can be used to compare several options and be integrated into a general decision-making process that considers how a choice will affect the environment. It is frequently used to estimate how alternative waste management strategies would affect the environment. According to ISO14040, conducting LCA is composed of four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation of findings, as shown in Figure 11.

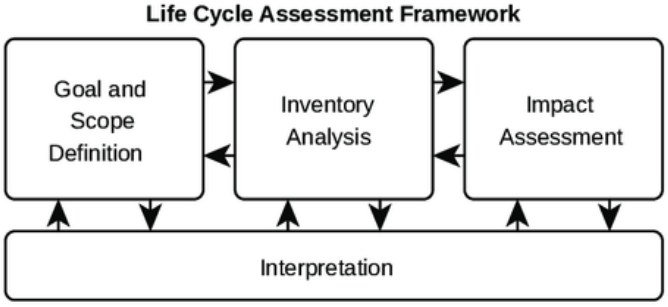


Figure 11. Life-cycle assessment framework.

3.1. Goal and Scope Definition

Goal and scope definition establishes the boundaries of the system under study. In this section, functional units are set, system boundaries are outlined, and research limits are determined [49]. The definition of functional units is extremely important. ISO14040 defines functional units as "quantified performance of a product system for use as a reference unit". All data collected and results will be related to the functional units, enabling a comparison of two or more scenarios based on similar function [50].

The scope of the LCA in this study is to assess the environmental impacts of different waste management scenarios. The study will cover five scenarios:

a. S1: Landfill; as shown in Figure 12. "System boundary for landfill scenario".
b. S2: Incineration with energy recovery; as shown in Figure 13. "System boundary for incineration scenario"
c. S3: Mechanical recycling with incineration of residuals; as shown in Figure 14. "System boundary for mechanical recycling scenario".
d. S4: Pyrolysis with incineration of residuals; as shown in Figure 15. "System boundary for pyrolysis scenario".
e. S5: Mechanical recycling and pyrolysis with incineration of residuals; as shown in Figure 16. "System boundary for mechanical recycling and chemical recycling".

The functional unit for each scenario is defined in Table 2.

Table 2. Functional unit and credit for the five different waste management scenarios under consideration.

Scenario	Functional Unit	Credit/Considerations
S1	1 kg of mixed plastic waste landfilled	None
S2	1 kg of mixed plastic waste incinerated	Electricity and heat substitution (1:1 substitution factor)
S3	1 kg of mixed plastic mechanically recycled, and residuals incinerated	Virgin PE(Polyethylene) and PP(Polypropylene) substitution (0.5 substitution factor)
S4	1 kg of mixed plastic waste chemically recycled, and residuals incinerated	Naphtha substitution (1:1 substitution factor)
S5	1 kg of mixed plastic waste mechanically and chemically recycled, and residuals incinerated	Virgin PE and PP substitution (0.5 substitution factor) and Naphtha substitution (1:1 substitution factor)

System boundaries for all scenarios are shown below:

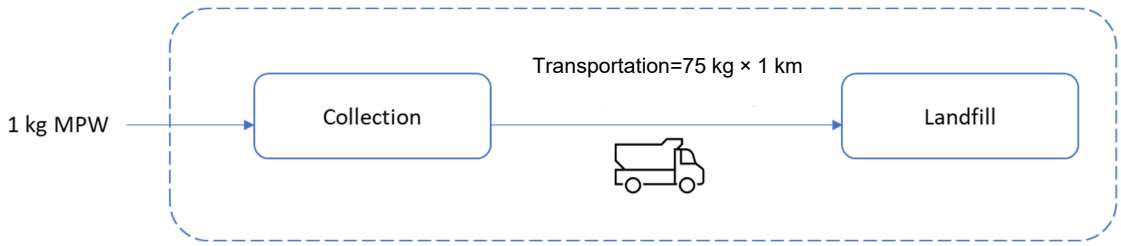


Figure 12. System boundary for landfill scenario.

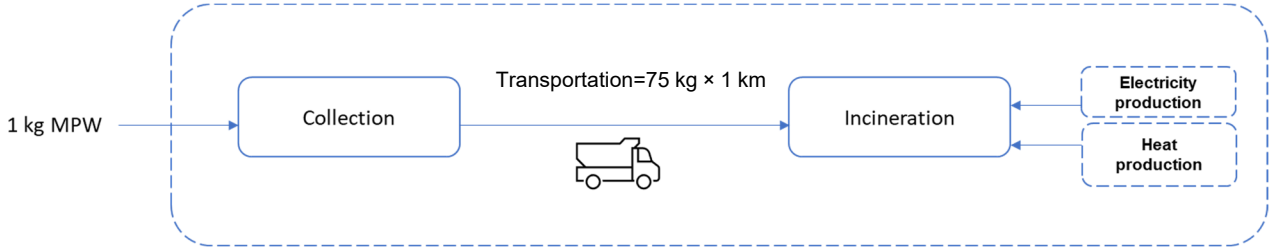


Figure 13. System boundary for incineration scenario.

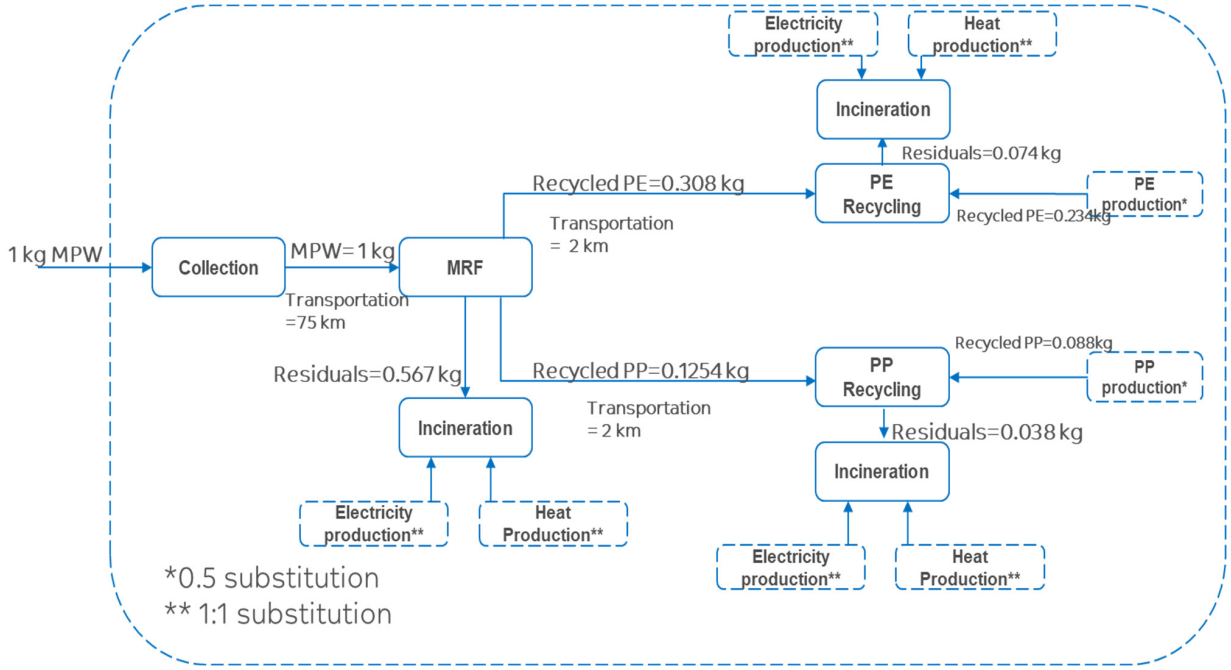


Figure 14. System boundary for mechanical recycling scenario.

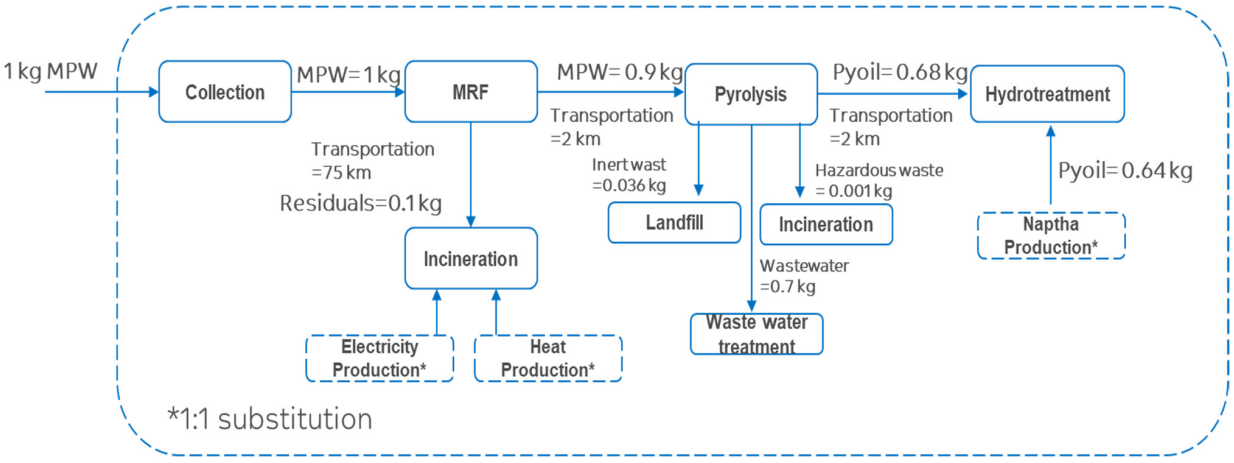


Figure 15. System boundary for pyrolysis scenario.

3.2. Life Cycle Inventory (LCI)

The composition of plastic waste varies from time to time and region to region. A characterization of plastic composition in the municipal solid waste in Saudi Arabia is not available in the literature. The composition of mixed plastic waste used in this study was based on the composition of mixed plastic waste provided by [51] as shown in Table 3. It is assumed that impurities such as organic waste, metals, glass, paper, and textiles are present in this waste stream which will need to be removed via MRFs (Material Recovery Facilities) for the recycling scenarios.

Regarding distances travelled for the landfill scenario, it is assumed that the mixed plastic waste is transported to Al-Sulay Landfill with an average distance travelled of 25 km. For incineration, mechanical recycling, and chemical recycling scenarios, it is assumed that all activities will be conducted in the Al-dughm site. The Al-dughm project was announced by the Royal Commission of Riyadh City [23] as a new project with state-of-the-art integrated waste management facilities that will be utilized in the future as the main waste management site in Riyadh. This project is still under development and will be located 75 km outside Riyadh [23]. Sources of data for this study are from the Ecoinvent 3.9.1 database for background data and

from published peer-reviewed reports and Ecoinvent 3.9.1 for foreground data. Background data in all scenarios are for the Saudi Arabia region. Foreground data are sourced from Ecoinvent 3.9.1 for landfill and incineration scenarios, Faraca et al. [52], in 2019 for mechanical recycling, and Viveros et al. [53] in 2022 for pyrolysis.

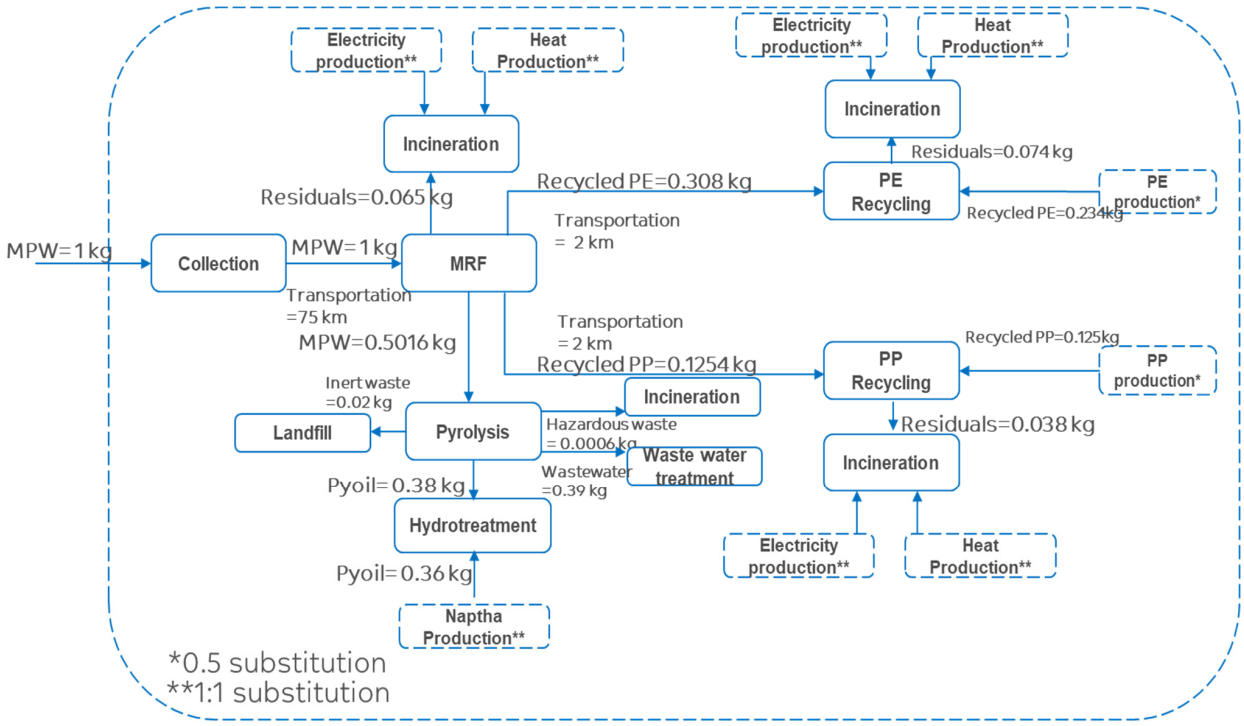


Figure 16. System boundary for mechanical recycling and chemical recycling.

Table 3. Composition of mixed plastic waste assumed in this study [51].

Polymer Type	Abbreviation	Composition
Polyethylene	PE	42%
Polypropylene	PP	14%
Polyvinyl chloride	PVC	6%
Polystyrene	PS	9%
Polyethylene terephthalate	PET	10%
Others		9%
Impurities		10%

4. Results

Vast consumption of plastics leads to a significant accumulation of plastic waste in landfills or nature, especially oceans. The implementation of a circular plastic economy is becoming more important owing to these challenges with the purpose of reducing, reusing, and recycling all plastic waste.

4.1. Base Scenarios

The LCIA (Life-Cycle Impact Assessment) categorizes the LCI results into groups of environmental issues or damages. To translate masses of compounds from the LCI results into typical equivalents of one category indicator, characterization models are used. The level of detail of which the results are presented depends on the choice of either mid-point or end-point methods. The level of details in the mid-point is higher than the end-point. Therefore, the choice of the method will primarily depend on the research objectives and intended audience. Mid-point indicators show the direct impacts, while end-point method show the resultant effect [54]. For all scenarios in this paper, mid-point indicators using CML-IA Baseline method were used, utilizing OpenLCA software. Figure 17 shows a

comprehensive analysis of the various waste management scenarios of LCA results which will be discussed later.

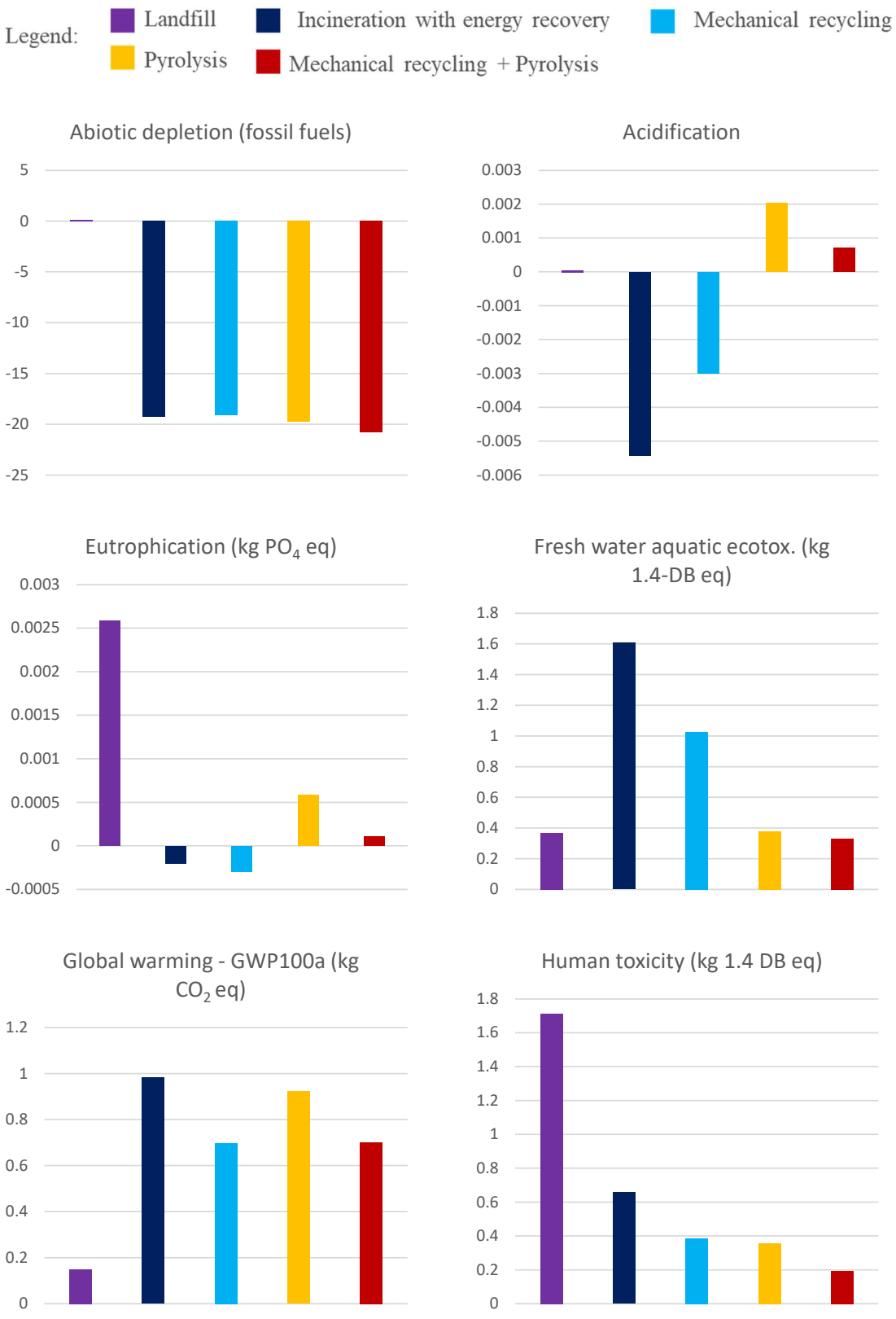


Figure 17. *Cont.*

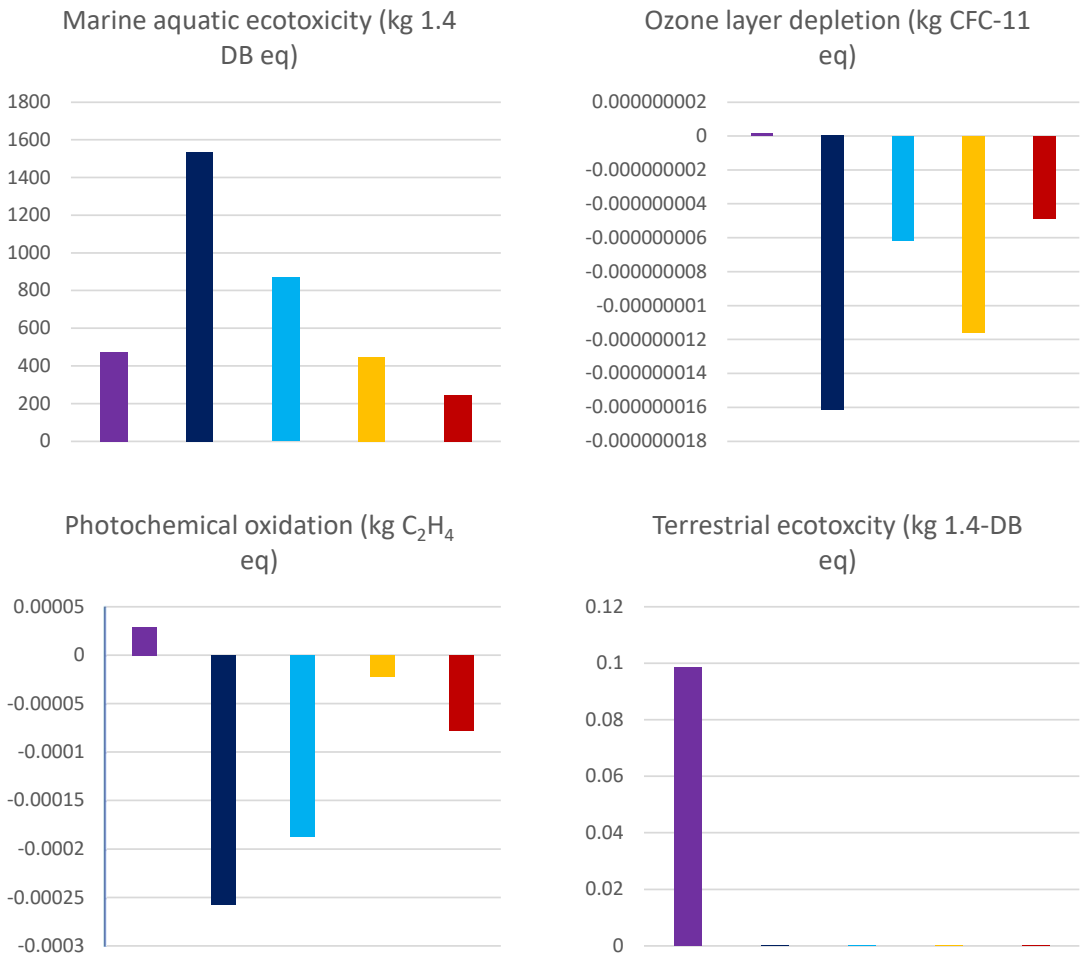


Figure 17. LCIA results for all cases per functional unit.

4.2. Sensitivity Analysis

Sensitivity analysis is vital for showing how variations to different assumptions made in the model can affect the outcomes, which can lead to more informed decisions [55]. Two factors were identified where sensitivity analysis will be made:

1. Substitution factor for recycled products;
2. Utilizing renewable energy sources for electricity to replace fossil-based electricity.

In this study, the maximum for each indicator was identified and set to 100%, and the results of the other variants are displayed in relation to this result. This can clearly show how much improvement is made for each scenario. Results that are positive show that they have an environmental burden, while results that are negative indicate environmental benefit for each impact category, as illustrated in Figures 18 and 19.

4.2.1. Substitution Factor

This term is used to describe how much virgin product can be replaced by recycled material. In the base case, the substitution factor was assumed to be 0.5. Higher substitution factors mean more virgin material is displaced by recycled material, which in turn can reduce environmental impacts of the system [56].

4.2.2. Renewable Energy

Recently, energy obtained from renewable sources, such as solar and wind, are becoming more competitive in terms of cost compared to fossil-based electric energy thanks to technological advancement in this field [57]. Many countries have pledged to be more carbon-neutral in the long term. Utilization of renewable sources of energy is critical to

decarbonizing the environment and reaching carbon neutrality. Figure 20 shows the effect magnitude of utilizing renewable sources of electricity to replace fossil-based electricity. Analysis was performed on all scenarios that consume electricity: mechanical recycling, pyrolysis, and mechanical recycling and pyrolysis.

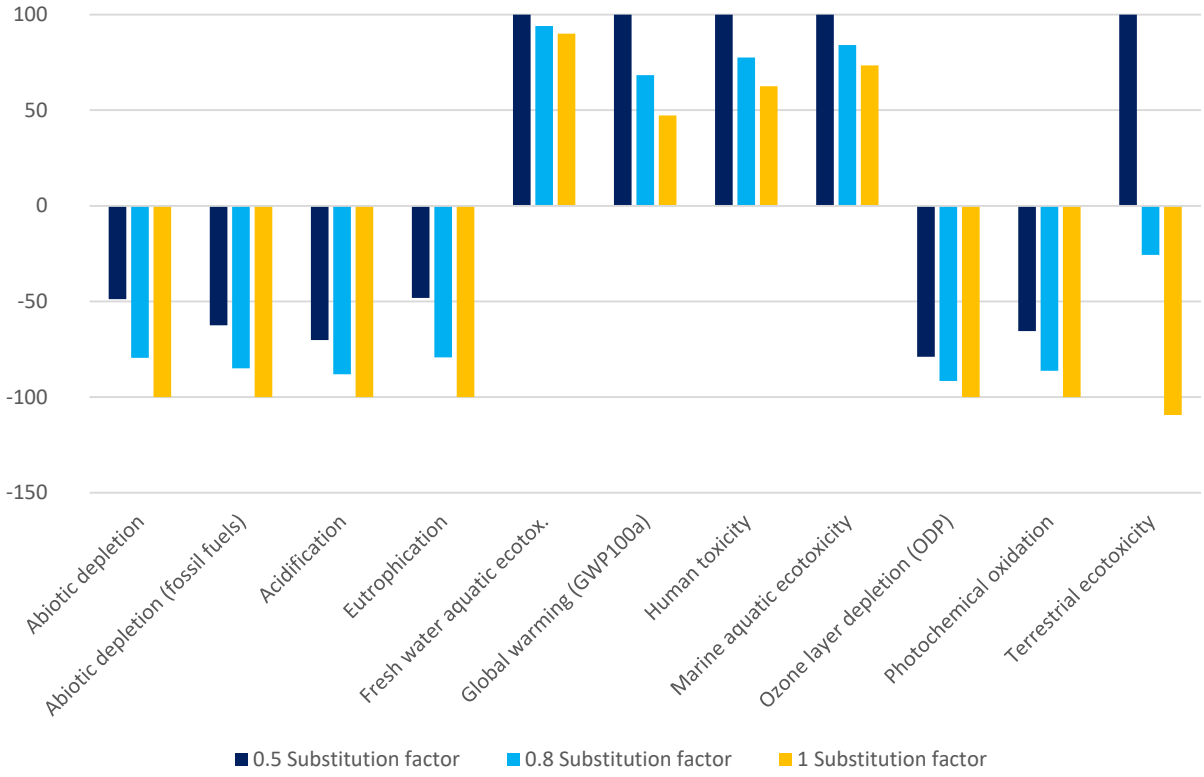


Figure 18. Sensitivity analysis on substitution factor for mechanical recycling scenario.

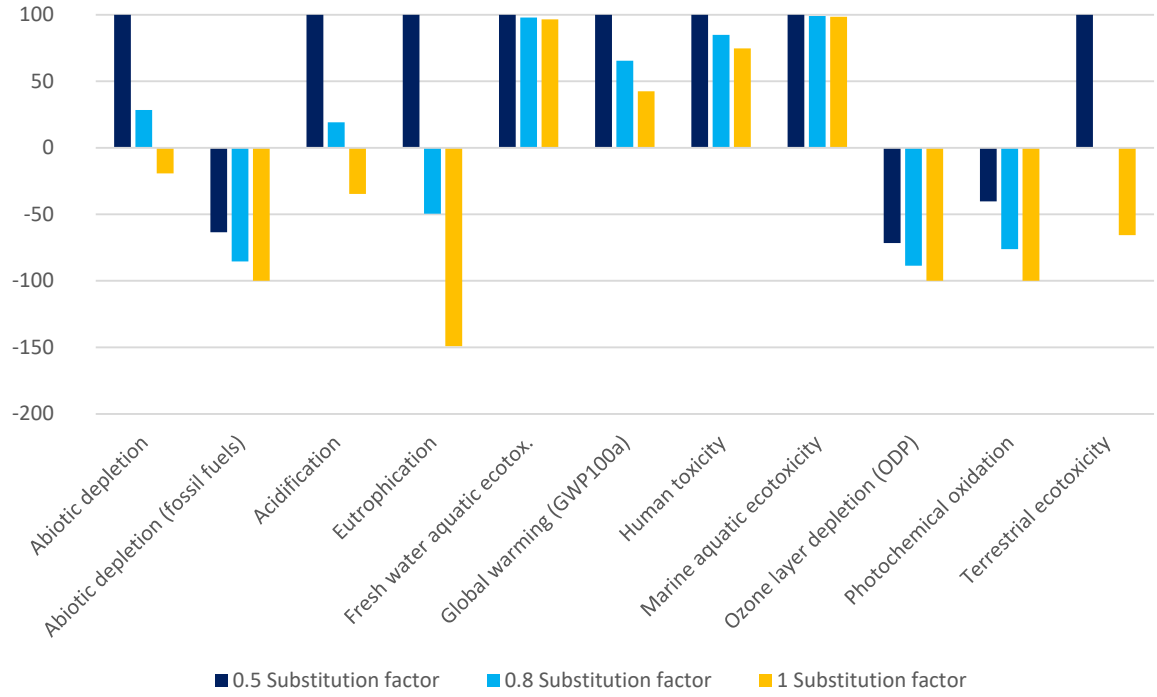


Figure 19. Sensitivity analysis on substitution factor for mechanical recycling and pyrolysis scenario.

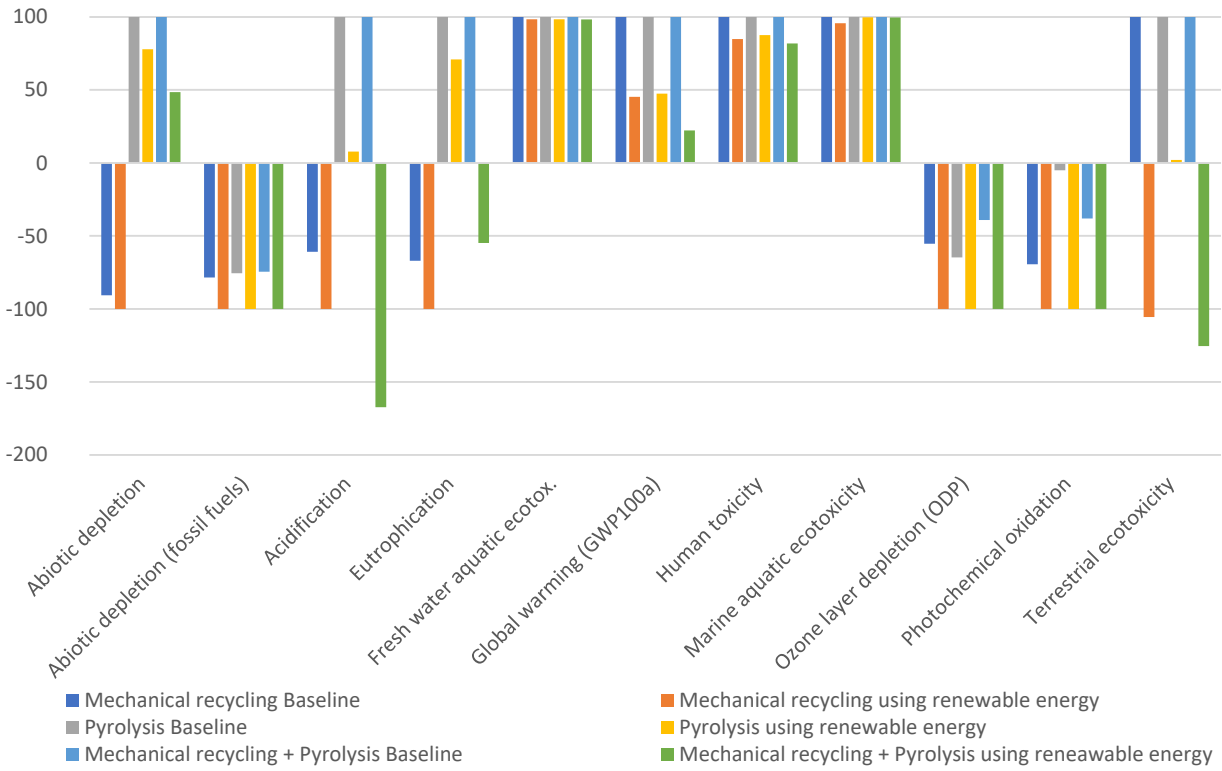


Figure 20. Sensitivity analysis showing effect of utilizing renewable source for electricity.

5. Discussion

In this section, a comprehensive analysis of various waste management scenarios of LCA results shown in Figure 17 will be provided. This evaluation will provide an assessment of various environmental impacts associated with each scenario, which will facilitate better understanding for policy makers and industry stakeholders to make more informed decisions.

The landfill scenario had a negative impact on all ten impacts category studies. This is because material is disposed of, and no value is extracted out of it. The landfill scenario had the worst impacts on abiotic depletion of fossil fuel, eutrophication, human toxicity, ozone layer depletion, photochemical oxidation, and terrestrial ecotoxicity. Although the immediate environmental impact of landfill is on collection and transportation, long-term impacts include contamination of ground water through discharging of harmful additives when plastic is degraded [58]. Leachate is considered one of the major problems associated with landfills that impact the environment. Leachate is a toxic liquid formed when rainwater percolates through the waste, through aqueous fluids present in the waste, and through biochemical processes occurring in the landfill waste [59]. The problem with leachate is that it can leak into ground water and contaminate it, which poses a significant health problem to the community [60].

Incineration with energy recovery had a negative environmental impact on five out of the ten indicators studied. It had the worst impact related to greenhouse gas emissions contributing to global warming. Incineration is energy-intensive and produces substantial amounts of flue gases, which are rich in CO_2 and other greenhouse gases. Flue gas, if not treated properly, can be damaging to the environment [61].

Mechanical recycling had a low environmental impact on acidification, eutrophication, and global warming potential compared to other scenarios. Mechanical recycling has been shown to be extremely sensitive to substitution factors, as shown in Figure 18. A higher substitution factor means that more virgin resin can be displaced by the recycled materials, which in turn reduces environmental burdens significantly across all impact categories. To increase the substitution factor, higher recycling product quality is required. This can be

achieved in numerous ways, including better sorting techniques to ensure that a high-purity product is obtained [62]. Another way to enhance recycled product quality is by using booster resins which function as compatibilizer of polymer blends that increases mechanical properties of the product [63]. However, mechanical recycling of plastics has some challenges. When polymers are reprocessed, they tend to degrade, causing final product properties to deteriorate. Degradation is caused by elevated temperature in the extruder, with the presence of oxygen yielding free radicals that initiate chain sessions. Moreover, some plastics are not compatible with each other, and the presence of contaminants in the recycled stream can be detrimental to final product properties [34]. When plastic properties are affected due to the recycling process, the only option is to utilize it in low-requirement applications, which is known as downgrading [58]. While mechanical recycling shows potential as a short-term way to recover value from waste, its restricted cycle count and eventual material degradation make the process inadequate for long-term product value retention in the plastic economy. Finally, the use of renewable source of energy for electricity has been shown to be extremely beneficial to reduce the process environmental burdens across all indicators with varying magnitude, as shown in Figure 20.

Pyrolysis was shown to have low environmental impacts compared to other scenarios in terms of abiotic depletion of fossil fuels, freshwater aquatic ecotoxicity, human toxicity, and marine aquatic ecotoxicity. However, it has a high environmental impact on acidification and eutrophication, which is driven by using urea as an additive. It might be worthwhile for future studies to consider alternative additives for pyrolysis and assess their environmental impacts using LCA. Pyrolysis has several advantages: first, upcycling waste plastic into useful value-added products, promoting a circular economy. Products can be used in applications equivalent to ones produced from virgin polymers, such as food contact applications [64]. Secondly, it provides an alternative source of energy, since the process of pyrolysis provides fuels as by-products, which will reduce the dependency on fossil fuel term [65]. Thirdly, it eliminates the material degradation that occurs during mechanical recycling, guaranteeing that material value is kept within the plastic economy for the long term [66]. Finally, pyrosis process is less sensitive to dirty waste streams and the presence of composite materials compared to mechanical recycling [66]. The drawbacks of pyrolysis are that it is energy-intensive and requires additional processing steps after plastic molecules are broken down, causing the process to be costly and impacting its economic feasibility [67]. In addition, pyrolysis is sensitive to some types of polymers, such as polyethylene terephthalate, which contain oxygen in the polymer backbone. Release of the oxygen molecules from polymers in the process can affect the process' efficiency [64].

Combining mechanical recycling with pyrolysis seems to leverage the strengths for each method. As discussed earlier, mechanical recycling has better performance in acidification, eutrophication, and global warming. On the other hand, pyrolysis performs well in the abiotic depletion of fossil fuels, freshwater aquatic ecotoxicity, human toxicity, and marine aquatic ecotoxicity. Therefore, the combined scenario improves the environmental impacts across multiple impact categories. In the combined scenario, mono-polyolefin streams are sent to mechanical recycling while mixed plastic waste is sent to pyrolysis. This is the best option, since mechanical recycling is more sensitive to blends and requires robust separation to increase the final product quality. Therefore, the combined scenario can accept a broader range of plastic waste, which improves the overall waste management system towards shifting to a circular economy. In addition, the combined scenario means that more plastic waste can be managed, which reduces the dependency on landfill and incineration. It is also recommended to utilize renewable energy for electricity generation. As can be seen in Figure 20, it has a significant impact across all impact categories. For the combined scenario, abiotic depletion is reduced by more than 50%. Acidification, eutrophication, and terrestrial ecotoxicity have become overall environmental benefits while the baseline is an environmental burden. Finally, global warming potential is reduced by 80% compared to baseline.

6. Conclusions

For waste composition by type, it was found that Saudi Arabia has a much higher percentage of organic food waste compared to the global average. This was attributed to high GDP per capita, local traditions that encourage preparation of massive quantities of foods during celebrations, and lack of public awareness. Current waste management practices in Saudi Arabia differ greatly from that of OECD countries. Disposal in controlled landfills is considered the primary waste management technique in Saudi Arabia, accounting for 85% of the total waste. On the other hand, landfill proportion in OECD countries is around 40%. In Saudi Arabia, recycling accounts for the remaining 15% of total waste management, driven by an informal sector which gathers and separates paper, plastic, and metallic material waste from MSW. In OECD countries, varying percentages are seen across regions, with waste being managed mainly through recycling, composting, and incineration.

The calculation of environmental impacts of several waste management scenarios was performed using LCA. The scenarios that were analyzed were landfill, incineration with energy recovery, mechanical recycling, pyrolysis, and a combined case of mechanical recycling and pyrolysis. The landfill scenario was worse than all other options, underperforming in most impact categories. Incineration with energy recovery had a lower environmental impact than landfill and higher than the other scenarios. It contributed the most to global warming potential since it is energy-intensive and produces substantial amounts of flue gases, which are rich in CO2 and other greenhouse gases. The combined case of mechanical recycling and pyrolysis was the best option from many dimensions. It had the lowest overall environmental impact compared to all other cases, since it leverages the strengths of each method complementing each other. It also can contribute to greater implementation of circular economy by accepting a wider range of recycling materials with varying quality. It is recommended that mono high-quality plastics be sent to mechanical recycling while mixed plastic waste is sent to pyrolysis. It is also more practical, since mechanical recycling is limited to the number of cycles, contributing to material degradation. The results show the need to improve the public awareness regarding the end of life of plastics, which includes sorting and recycling and waste management technologies. While pyrolysis is more energy-intensive, it can complement mechanical recycling by upcycling plastic waste to virgin-grade products. Sensitivity analysis revealed that increasing the substitution factor has the significant benefits of reducing product environmental impacts. This can be achieved by enhancing recycling material quality through utilizing better sorting technologies and addition of booster resins. Finally, the utilization of renewable sources of electricity to replace current fossil-based electricity in Saudi Arabia has been shown to be extremely beneficial to reducing plastic waste management processes environmental burdens across all indicators with varying magnitudes.

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