LIFE CYCLE ASSESSMENT OF MUNICIPAL SOLID WASTE MANAGEMENT OPTIONS IN PESHAWAR

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DEDICATION

To accomplish anything challenging, we need to put in the time and work on our own and listen to the advice of our elders, particularly those we hold dear.

My modest efforts are dedicated to my doting mother, who gave me all they had in the form of love, support, and prayers day and night and made it possible for me to succeed academically and earn this honour, as well as to all of my hardworking and respected teachers.

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ABSTRACT

Peshawar being a developing city of Pakistan generates 967 tons/day of waste. Effective municipal solid waste (MSW) management system is needed in this city since the collected waste is dumped in an open dumping site causing adverse environmental impacts. A secondary data has been obtained from the Water and Sanitation Services Company, Peshawar for a period of one year. This study included the categorization of MSW into several groups, namely biodegradable, combustible, plastics, and others. 1 tonne of MSW has been selected as the functional unit. The system boundary included treatment and disposal of MSW via various methods such as open dumping, incineration, and anaerobic digestion. Four different scenarios were developed as alternatives to the current waste management practice. For inventory data, Ecoinvent database in SimaPro version 9.3.0.3 is used. The data underwent evaluation using the RiCiPe 2016 methodology, employing midpoint impact categories as well as endpoint damage assessment categories. Based on the findings, S1 (open dumping), current MSW management practice in Peshawar, has exhibited the most significant adverse effects on both midpoint and endpoint impact categories followed by S2 (sanitary landfill). Conversely, S5 which involved the anaerobic digestion of biodegradable waste, incineration of combustible and plastics, and diversion of the remaining waste to the landfill, has demonstrated superior performance. Additionally, the findings of the sensitivity analysis done on plastic waste indicated their segregation and recycling the recyclable components can reduce the environmental burden. This research demonstrated the LCA as a beneficial tool for governors and managers in devising an integrated waste management strategy that yields more favourable environmental benefits.

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Chapter 1

1. INTRODUCTION

Rapid urbanisation, economic expansion, the industrial revolution, the overexploitation of natural resources, and the depletion of fossil fuels were all hallmarks of the turn of the 21st century (Kaltsa, 2016). The management of municipal solid waste (MSW) has long been seen as a pressing global concern. While challenges in underdeveloped nations stem primarily from institutional shortcomings and public knowledge of the problem, in the developed world, worries about MSW management stem from vast resource use and unparalleled disposal (Bogner et al., 2007). The people who live in the world's least developed areas still have to deal with the consequences of poor MSW management practices and lack access to adequate trash collection and disposal services.

The management of MSW in several developing nations involves the collection and subsequent disposal in landfills, as highlighted by Jara-Samaneigo et al. (2017). This practice often lacks energy recovery mechanisms or gas control measures, resulting in adverse consequences for public health and the environment. These include the emergence of community health issues and the imposition of environmental burdens such as greenhouse gas (GHG) emissions, as well as pollution. The improper management of MSW via practices such as open dumping, and landfilling poses significant challenges to both human health and the environment (Khandelwal et al., 2019). It is well acknowledged that each step within the management system of MSW, including waste collection, disposal, and waste-to-energy (WtE) processes, is associated with the discharge of emissions into the air, water, and solid waste (Rajceifar et al., 2015).

Sustainable waste management and energy recovery are possible via the use of WtE technologies such incineration, gasification, pyrolysis, and anaerobic digestion (Arena et al., 2015; Evangelisti et al., 2015; Kumar et al., 2020). In addition, material recovery is an effective and environmentally friendly method of managing garbage (Cimpan et al., 2015; Goulart Coelho and Lange, 2018).

With a yearly urbanisation rate of 3.2% (Ameer and Munir, 2016), Pakistan is a growing country that also produces over 50 million tonne of MSW, with a growth of 2.4% per year (International Trade Administration, 2022). Agriculture waste, hospital waste, MSW, animal waste, and marine litter are only some of the types of garbage it gets annually (Mohsin and Chinyama, 2016). Unfortunately, much of the trash ends up rotting in open dumps, uncontrolled dumpsites, or freshwater areas without garnering any serious anxiety over its management. The country's urban waste management practices are inadequate and poor (Shehzad, 2016), while rural residents still lack access to garbage pickup. Most inhabitants are compelled to dump household garbage in the open, causing major issues about environmental health and aesthetics, due to institutional failings on providing facilities about adequate MSW collection, treatment, and disposal.

Cities can be helped by MSW management initiatives, such as waste collection and disposal at authorised landfills, but the problem of dwindling landfill space continues to pose serious environmental pressures (Shane and Gheewala, 2017).

Waste at landfills that are not regularly checked for leaks releases methane, a potent greenhouse gas that contributes to global warming (World Bank, 2012). In addition to being a hazard to the environment, landfill garbage also poses a threat to human health, and depleting natural resources (Laurent et al., 2014). The implications of MSW dumps on climate change and sustainability have not been prioritised in any waste management system. There were 22 metric tonnes of CO_2 equivalent released into the atmosphere due to waste in Pakistan in 2018 (Asian Development Bank, 2021). Those countries who joined the Paris Climate Agreement committed to lowering their greenhouse gas emissions by 2030, subject to international funding (Asian Development Bank, 2021).

The lack of a reliable and affordable energy supply is a problem in both rural and urban Pakistan. There must be a harmony between energy production and consumption as the economy expands (Raheem et al., 2016). Since around ten years ago, Pakistan has been experiencing a severe crisis due to an energy shortage (Javed et al., 2016). Many studies have been undertaken to examine the different renewable energy options' ability to fill the energy gap. The MSW industry has received less focus in the past in an effort to solve Pakistan's energy dilemma.

In order to ensure the continued health of Pakistan's ecosystem, economy, and society, sustainable planners will need to implement effective solid waste management techniques. Only by rigorous use of such technology, policies, and tactics can their long-term advantages be realised.

Peshawar, the provincial capital of Khyber Pakhtunkhwa and the sixth biggest city in Pakistan, produces 967 tonnes of MSW per day. Peshawar's urban regions (52 of the city's Union Councils out of total 92) are serviced by the Water and Sanitation Services Company, Peshawar

(WSSP), a municipal entity. Since 2018, garbage collected in Peshawar's metropolitan districts has been trucked 26 kilometres outside of the city and open dumped in the area of Shamshatoo, Peshawar.

Figure 1 Open Dumping Site at Shamshatoo, Peshawar (Source: Tribal News Network)

Peshawar being part of the "Khyber Pakhtunkhwa Cities Improvement Project" that was launched by the provincial government in 2021, a sanitary landfill (at Shamshatoo, Peshawar) was proposed and is already in the implementation stage.

Table 1: Basic Data (Source: Asian Development Bank, 2022)

Project Name: Khyber Pakhtunkhwa Cities Improvement Project	
Project Number: 51036 - 002	**Approval Number:** 4160/8412/0816
Country: Pakistan	**Executing Agency:** Local Government Elections and Rural Development Department
Project Financing Amount: US$ 650,000,000 **ADB Financing:** US$ 385,000,000 **Cofinancing (ADB Administered):** US$ 200,000,000 **Non-ADB Financing:** US$ 65,000,000	**Implementing Agency:** Water and Sanitation Services Company – Mingora Swat Water and Sanitation Services Company – Abbottabad Water and Sanitation Services Company – Kohat Water and Sanitation Services Company – Mardan Water and Sanitation Services Company – Peshawar **Project Closing Date:** 30 June 2028
Date of First Procurement Plan: 10 December 2021	**Date of this Procurement Plan:** 19 May 2023, Version 5
Procurement Plan Duration: 18 Months	**Related to COVID-19 response efforts:** No
Advance Contracting: Yes	**Use of e-procurement (e-GP):** No

Figure 2 On-going Construction of Sanitary Landfill at Shamshatoo, Peshawar (Source: WSSP Linkedin Profile)

The present research is urgently required to help managers and policymakers in Peshawar effectively manage MSW. The purpose of this study is to evaluate the ecological effects of the "business as usual" or "baseline scenario" i.e., open dumping of MSW. A comparison of baseline scenarios with alternate MSWM options will be carried out. The technique of Life Cycle Assessment (LCA) is finding more and more uses in different areas of life, thanks to the growing interest in sustainability and sustainable solutions. LCA attempts to assess the environmental impacts of a product throughout its entire life cycle, from the mining of raw materials to its final disposal or reuse. There has not been any LCA research on waste management strategies in Peshawar. Therefore, this research provides a potential new way to combine LCA with SMW. Based on the LCA findings, implementation of the most viable strategy(ies) for controlling MSW would be suggested. Peshawar has not yet investigated these sorts of choices and methods in the field of ecological worry.

Putting this research's findings to use in Peshawar, Pakistan's solid waste management industry is a worthwhile endeavour. Sustainable management practices may be developed when the best MSW management options are evaluated, providing opportunities for innovation. The utilisation of MSW as a source of energy generation is another potential outcome of this. As a result, we'll be that much closer to achieving the Sustainable Development Goal. Action on climate change (SDG 13), a part of Goal 11 for sustainable cities.

The current study is being conducted under the following objectives:

1. Evaluation of environmental impacts of existing MSW management practice in Peshawar.
2. Comparison of environmental impacts of existing MSW management practice with alternate MSW management options through LCA approach.

The following advantages can be gained from the study:

1. The findings would enable the selection of the MSW management option(s) with the least negative impact on the environment.
2. Be familiar with the environmental risks and issues caused by current MSW management methods.

The present investigation may be used outside national borders in the following areas::

1. Solid Waste Management
2. WtE Generation
3. Climate Change Adaptation
4. Global Warming Control

Chapter 2

2. LITERATURE REVIEW

2.1. General

The term MSW is commonly used to refer to all the trash collected and disposed of by the local government. This includes debris from both residential and commercial/industrial areas. Rapid population increase, economic development, and urbanization exacerbate MSW generation and related management challenges. The World Bank estimates the yearly rate of worldwide MSW creation to be 2.01 billion tonnes, with a rise to 3.4 billion tonnes through 2050. (Kaza et al., 2018).

"Waste management" refers to the coordinated process of trash hauling, sorting, treatment, disposal, or recycling (Silva et al., 2021). With an expected annual growth rate of 2-3% in emerging nations, MSW output has increased from 0.49 billion tonnes in 1997 to an estimated two billion tonnes in 2007. (UNEP, 2009). MSW management is always a municipality's duty.

2.2. Historical Development in Waste Management

Nearly all of our activities generate waste. Digging trenches in the backyard or on the fields was the standard method of garbage disposal in the past. Since there weren't very many people living there, to begin with, and there was plenty of space to dump garbage, this wasn't a significant issue. Yet while it has the potential to lessen waste and boost crop quality, garbage collection has become an essential issue for everyone as urban areas and suburbs proliferate (Christensen et al., 2020).

Open pits and landfills were the primary garbage disposal methods for ancient societies like the Romans and Greeks (Ali, 2015). Unsanitary conditions and disease outbreaks were commonplace due to waste dumping into rivers and streets throughout the Medieval Ages (Ojeda-Bentez et al., 2019). Significant developments in waste management occurred in the 19th century when municipal authorities began to control trash disposal and develop new methods for waste treatment in response to the growing number of urban centres (Hickman et al., 2016).

By the 1920s, several towns had adopted incinerators to reduce garbage production; the first ones had been constructed in the early 1900s (Tchobanoglous et al., 2014). New waste management strategies, including recycling and hazardous waste disposal, emerged in the middle of the twentieth century in response to rising public awareness of environmental contamination (Brunner & Rechberger, 2015). The United States enacted the Resource Conservation and Recovery Act (RCRA) in the 1970s to control the dumping of hazardous waste, and its success spurred similar legislation in other nations (EPA, 2018).

As the world's population and standard of living have increased in recent decades, so needs effective waste management. New waste management solutions, such as WtE systems and zero-waste efforts, have been developed due to governments and organizations (UNEP, 2019). The circular economy, which aims to reduce waste by reusing and recycling materials, has also gained popularity (Kirchherr et al., 2017).

2.3. Worldwide Municipal Waste Production

A nation's standard of living significantly impacts the kind of materials that end up in MSW and how quickly it accumulates. Paper, plastic, and other non-organic materials comprise a larger share of the trash stream in high-income nations. In contrast, in poor and middle-income countries, organic waste makes up a disproportionate share of the garbage problem (Das et al., 2019).

Modern technologies such as thermal treatment sanitary landfills, (incineration, gasification, and pyrolysis), and biological treatment approaches (anaerobic Digestion (AD) and composting) are typically used in industrialized nations to manage MSW properly. These cutting-edge methods are expensive to implement and run but don't eliminate MSW's harmful effects. In addition, most MSW is still disposed of in developing nations by being burnt or dumped publicly or in landfills, with or without following gas and leachate treatment facilities. The environment and human health suffer when MSW is not adequately managed on a regional scale. Toxic gases, polycyclic aromatic hydrocarbons, poisons, furans, dioxins, particulate matter, volatile organic compounds, and other pollutants are released into the air when the trash is dumped or burned in the open, and landfills that aren't adequately maintained pollute the soil and water underneath them. Negative impacts on health, including respiratory and neurological illnesses, result from prolonged exposure to toxic gases (Kaza et al., 2018).

Leachates are harmful to aquatic life and humans when they are combined with potable water, according to research by Mukherjee et al. (2015). Managing garbage also adds to climate change, ocean pollution, and loss of natural resources. According to a number of studies, MSW accounts for between 3 and 5 percent of all human greenhouse gas emissions globally. (IPCC, 2014). The most common sources of direct greenhouse gas emissions are the combustion of rubbish (which releases CO_2) and the decomposition of organic waste in landfills (which releases methane; CH_4). Use of fossil fuels for energy and inefficient recycling of materials also contribute to indirect GHG emissions and resource depletion (Wang et al., 2020).

More than 2 billion tonnes of municipal solid waste are generated annually by the world's population (Kaza et al., 2018). Only around 38% of garbage is managed in a sustainable manner, via activities like recycling and energy recovery; the remaining 62% contributes to issues like climate change. According to a 2018 study by Kaza et al., the average daily solid waste production per person is between 0.11 and 4.54 kilogrammes.

Waste generation is linked to rising population, developing technologies, expanding economies, availability of recycling markets, and waste and carbon restrictions. When a country's economy grows, so does the amount of trash created by its citizens. The world's population is expected to reach 9.73 billion by 2050 (Worldometers, 2019), and as economic expansion throughout the world, particularly in Asian countries, picks up speed, so will waste production (Capuano, 2000). There will likely be 3.4 billion tonnes of municipal solid waste produced worldwide by 2050 (Kaza et al., 2018).

By 2040, rising population and economic activity are expected to raise energy consumption by 28%, necessitating an additional 739 quadrillion British thermal units (Btu) of energy. Therefore, in order to build a sustainable and clean environment, it is of the utmost importance to create new and advanced methods to lessen the negative environmental impact of poorly managed waste through more efficient waste management practices and the generation of surplus energy beyond the need energy demand.

Changing worldwide waste management regulations have been driven by the remarkable pace of MSW creation and its heterogeneous character. There has been a global shift in focus from only environmental conservation to including resource recovery and valorization, thanks to sustainability and circular economy (Pharino, 2017). Reducing waste at its source, reusing materials, recycling assets, recovering resources, and finally, disposing of unwanted items in landfills are all advanced management methods (Pourreza et al., 2020; Wang et al., 2020b). Reducing the environmental and physical costs of landfills and reaping environmental advantages through the retrieval of energy and bio-fertilizer are both possible through, for instance, the treatment and recycling of food waste (FW) using biological processes (Kaur et al., 2019).

With a current estimate of 4.028 billion, the global urban population is rapidly expanding at an annual pace of 2.035%. (World Bank, 2016a, 2016b). Rapid industrialization, economic, and urbanization expansion are the primary drivers of global MSW growth due to the massive rise in the human population. Waste generated by urban residents is expected to almost double from 3.5 million metric tons/day in 2002 to 6.1 million metric tons/day in 2025, costing an estimated $375 billion to properly manage (World Bank, 2012).

Only social, economic, and environmental variables influence the composition and production rate of municipal solid waste. Higher GDP nations create more rubbish overall, and this garbage is more likely to be formed of nonbiodegradable materials like paper and packaging, compared to garbage generated in lower GDP countries. The inefficient and filthy disposal of MSW by open burning, unsanitary landfilling, and open dumping exacerbates a number of environmental difficulties (Laurent et al., 2014). These include global warming, human health risks, ozone depletion, abiotic resource depletion, ecological damages, etc. The public's unwillingness to accept proposed new waste treatment facilities is influenced by this. Risk assessment is essential in the MSW management decision-making process for mitigating the aforementioned effects.

2.4. Municipal Solid Waste Generation and Management in Pakistan

The urban population of Pakistan is expected to grow to 118 million by 2030 (UN-Habitat, 2019). The rate of municipal solid waste (MSW) generation has grown dramatically as a result of this fast urbanisation, and it is projected to reach 65 million tonnes by 2025 (World Bank, 2016). The country's MSW issue has been exacerbated by inadequate waste management infrastructure, inefficient garbage collection and transportation systems, and a lack of public awareness.

Only half of Pakistan's urban population uses regular rubbish collection services, according to a 2016 World Bank research. Up to 27 percent of urban garbage is collected and recycled by the informal sector every year (UNDP, 2020). This informal industry, however, is often unregulated, and the trash is typically dumped in uncontrolled dumpsites, leading to environmental contamination and public health problems (Asif et al., 2019).

Current waste management in Pakistan is mostly based on a linear model of garbage collection and disposal, as stated by Asif et al. (2019). This method, however, cannot be maintained, hence Pakistan must adopt a circular economy model if it wants to solve its MSW issue. Reducing trash production, reusing and recycling waste materials, and recovering energy and resources from garbage are all components of the circular economy concept.

Asif et al. (2019) note that expanding waste management infrastructure including WtE plants, recycling centres, and composting facilities is necessary for implementing a circular economy model. However, a developing nation like Pakistan may struggle to afford the time and resources needed to create such infrastructure.

To overcome these challenges, Asif et al. (2019) recommended adopting a public-private partnership (PPP) model for waste management in Pakistan. The PPP model involves the public and private sectors collaborating to provide waste management services. The private sector can bring in the required financial investment and technical expertise, while the public sector can provide the regulatory framework and oversight.

Due to insufficient waste management infrastructure, inefficient garbage collection and transportation systems, and low public awareness, Pakistan is experiencing a severe MSW issue. It's possible that the only way out of this issue is to embrace a PPP model for waste management and implement a circular economy. Pakistan's waste management infrastructure has to be developed, but this requires substantial investment and technical competence.

2.4.1. Open Dumping

Open dumping, which involves waste disposal in uncontrolled and uncovered areas, is a significant problem in Pakistan. It leads to waste accumulation, posing significant environmental and health risks (Ali et al., 2021). Open dumping sites attract scavengers and stray animals, which further contribute to the spread of diseases (Ali et al., 2021). Furthermore, as organic rubbish decomposes in open landfills, CH_4 is created, a powerful greenhouse gas that contributes to climate change (Khan et al., 2021).

There has been little progress in Pakistan in developing viable alternatives to open dumping as a means of waste management (Nisar et al., 2021). There has been a dearth of investment in waste management infrastructure (Shahzad et al., 2020), and there have been little efforts to encourage trash reduction, recycling, and composting. A significant portion of waste management in Pakistan is carried out by the unregulated and potentially hazardous informal trash industry (Nisar et al., 2021).

2.4.2. Landfilling

The place where garbage is dumped is known variously as a landfill, dump, tip, trash dump, dumping ground, or waste dump. Despite not beginning to systematically bury such garbage with daily, central, and ultimate covers until the 1940s (Hird, 2013), landfills remain the oldest and most extensively utilised form of rubbish disposal.

By using a number of technical and operational measures to keep the garbage contained and out of the surrounding environment, sanitary landfills help reduce environmental pollution and health risks. "an engineered method of disposing of solid waste on land in a manner that protects human health and the environment" (EPA, 2021).

2.4.3. Anaerobic Digestion

Recent years have seen a rise in interest in an alternate approach for treating MSW known as anaerobic digestion (AD). In anaerobic digestion (AD), biogas and a nutrient-rich residue called digestate are produced from the decomposition of organic waste in the absence of oxygen (Ahmed et al., 2020). AD provides several benefits over more conventional waste management strategies. When properly implemented, it may greatly reduce waste volume and weight, provide renewable energy, and offer a nutrient-rich fertiliser for agricultural use (Aziz et al., 2020).

2.4.4. Incineration

Implementing incineration (IN) as an MSW management method in Pakistan faces several challenges. One of the main challenges is the lack of proper infrastructure and technology for IN. Most cities in Pakistan do not have incineration facilities, and the existing facilities are outdated and poorly maintained (Khan et al., 2019).

Furthermore, another challenge is the lack of public awareness and acceptance of (IN) as a safe and sustainable waste management method. Due to the lack of trust in government authorities, there is a fear among the public that IN may cause health hazards and environmental pollution (Khan et al., 2019).

2.4.5. Integrated Solid Waste Management

Integrated solid waste management (ISWM) is thought to have evolved through time based on references to previous works in the field. In the 1660s, for instance, several European kingdoms outlawed cotton and linen for funeral shrouds so that more material could be used to make paper (Somani et al., 2021). As early as 1896, East London was home to the world's first municipal garbage incineration and energy generation facility. Until the early 1890s, New York City discharged most of its garbage into the Atlantic Ocean, despite complaints from New Jersey and New York's beach resorts because of the pollution it caused. The city then developed a source separation programme on the theory that separating garbage at the point of generation would allow it to recoup part of the collection expenses via the resale and reprocessing of commodities. In contrast, combined refuse would limit disposal possibilities to zero. The "Zabbaleen," a small ethnic group in early 20th-century Cairo, Egypt, were among the earliest places in the world to implement comprehensive waste management systems that prioritized recycling and reuse (Somani et al., 2021).

In the field of solid waste management, the meaning of the word "integrated" has been up for considerable discussion. Asefi et al. (2019) state that this expression is often used in SWM jargon. They argued that the term "integrated management" should be reserved for situations in which several portions of a system, activity, plan, or element are organised or designed to work together towards a common goal.

Tchobanoglous and Kreith (2002) define ISWM as an all-encompassing approach to waste management that uses a wide range of measures, including waste avoidance, recycling, combustion, composting, collection, and disposal programmes, to attain predetermined waste management aims and objectives. To effectively preserve public health and the environment, these tasks require careful planning, finance, collection, and conveyance. An efficient ISWM system prioritizes analysis of SWM, waste avoidance, and recycling options before settling on the best course of action.

2.5. Methods for Assessment of Waste Management

The environmental challenges associated with MSW management have been well recognised since the late 1960s (Zhang et al., 2021). Waste management is becoming more complicated, making it more difficult to choose the best approach. Therefore, systematic evaluations have given rise to mathematical models. It seems that in traditional models, economic optimisation is given more weight than its potential environmental effect. There has now been a shift in IWM planning towards a greater focus on minimizing adverse environmental effects while maximizing the reuse of resources like water and electricity. There has been a shift in recent years towards considering both economic and ecological considerations (Zhang et al., 2021).

Many new evaluation techniques are available now to help with waste management choices. Procedure- and analysis-based tools are the most common types of assessment instruments (Wrisberg et al., 2002). Procedures and decision-making contexts in society and the natural world are universal applications of technologies like the Environmental Management System (EMS). The latest technologies (like LCA) typically supply data that may be used in various contexts, including system optimization, alternative analysis, communication, etc. Nonetheless, analytical tools are often used with procedural tools (Joca, 2022).

The decision context determines the appropriate decision-making instrument to utilize. Certain factors can affect which tools are used in a given decision setting, while others can have a more significant impact. The topic of research (such as products, services, plans, policies, regions, organizations, etc.) and the effects of interests play significant roles in determining the most effective method to use in any given situation (environmental, economic, social, etc.). Yet, a variety of factors may affect the final decision on a tool to utilize. Several of these may also have an impact on whatever instrument is selected. Examples include choice and preference size, believability, cultural context, and degree of granularity and depth (Finnveden and Moberg, 2005).

Depending on the gravity of choice, more or less time and effort may be devoted to the investigation. In turn, this may affect how the instrument is employed. Both site-specific and non-site-specific data might be helpful in the decision-making process. Specific evaluation methods are more suited to objects in one place, while others may be utilized in a wider variety of items. An RA or EIA, for instance, would be more appropriate for a site-specific assessment if the decision maker were worried about local consequences, such as when choosing a site for a trash incinerator. But if you want to evaluate the environmental effects of various waste management strategies (recycling vs incineration, for example), an LCA or another life-cycle-based assessment tool is what you need (Alhazmi, 2021).

To that end, complementary results from many technologies are possible. Combining the findings of an EIA research with those of a LCA, for instance, might provide more insight from that perspective (Torkayesh et al., 2022).

2.6. Life Cycle Assessment

Life-cycle assessment (LCA) is the study of a product's or service's possible environmental consequences throughout the duration of its full life cycle (Guinee et al., 2011).

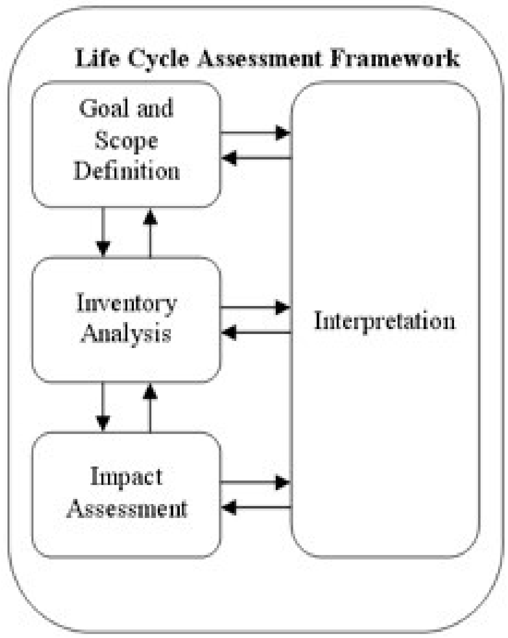

Figure 3 Life Cycle Assessment Framework

LCA is a viable method for evaluating the environmental impacts of waste treatment systems (Evangelisti et al., 2015). Because of its comprehensive, all-encompassing nature, LCA is useful for identifying the environmental repercussions (such as human toxicity, acidification, global warming, and ecotoxicity) that occur at different stages of a waste treatment system. The logical conclusion is to favour acts having less of an impact on the environment and shun those with better outcomes. After an LCA compares different waste treatment methods for particular wastes (Iqbal et al., 2020), a technique with lower environmental implications and high resource recovery may be chosen.

In addition, a wide range of organizations has developed the LCA approach over the past few decades, including the International Organization for Standardization (ISO) (Cleary, 2009). Goal and scope definition, effect assessment, inventory analysis, and interpretations are the four pillars of the LCA methodology established by the ISO 14040 series, which also provided updated standards and recommendations for LCA in 2006. (Cleary, 2009). Many literature reviews have been written about how LCA may be used in MSW management. Yet, they tend to concentrate on one type of garbage or garbage disposal.

2.6.1. Goal and Scope

The first phase of a life cycle assessment (LCA) is goal and scope definition, which, per ISO 14044, must be clearly stated and consistent with the application for which the research is designed. Due to the repetitive nature of LCA research, it may be necessary to narrow the focus of the study as it develops. The following criteria serve as the basis for the purpose of LCA research:

- Both the study's intended use and the rationale for conducting it should be included.
- The intended audience for whom the findings of the research are to be released; and the planned use of the data for establishing comparisons with other situations (ISO 14044, 2006).

Nearly 90% of Life Cycle studies devoted to solid waste management assess and contrast the efficacy of two or more potential treatment options. Sixty-three percent of these research evaluate regional policy framework in relation to the proposed waste management hierarchy by comparing actual ways to hypothetical approaches or technologies. Additional LCA research has been conducted to compare various LCA tools, assess the effects of system boundaries and data quality on results, and evaluate the impacts of a particular category (such as global warming potential) or waste type (such as food waste).

Similarly, the following needs should be clearly identified to determine the extent of an LCA study:

2.6.2. Functional Unit

In order to standardise the input and output data, it is helpful to have a measured and specified amount to use as a "functional unit." The nature of the flows under consideration is determined by this factor. According to ISO 14044 (2006), all such flows must be measured in the same functional unit and serve the same purpose.

Sixty percent or more of the LCA studies on municipal solid waste use "1 tonne of MSW" as the functional unit since it is unit based and very simple. Next, in 35% of LCA studies on MSW, the "Amount of MSW generated by a community/city" is included, despite its complexity in terms of computation. Functional units for LCA of MSW have also been examined in other research (Iqbal et al., 2020), both as inputs (the quantity of MSW entering a treatment facility) and as outputs (the amount of energy recovered).

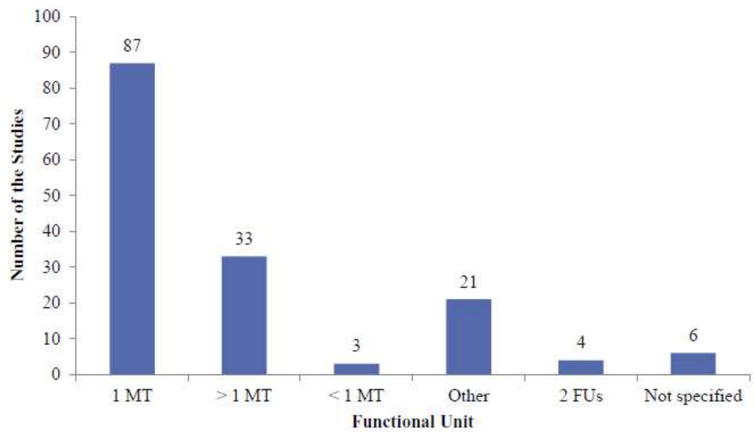

Figure 4 Number of Studies Showing Usage of Functional Unit

2.6.3. System Boundary

The inclusion or exclusion of a unit process from LCA is determined by its location inside the system boundary. Depending on the focus of the research, some subunit procedures may need to be included or excluded. In addition, it incorporates the time horizon (ISO 14044, 2006).

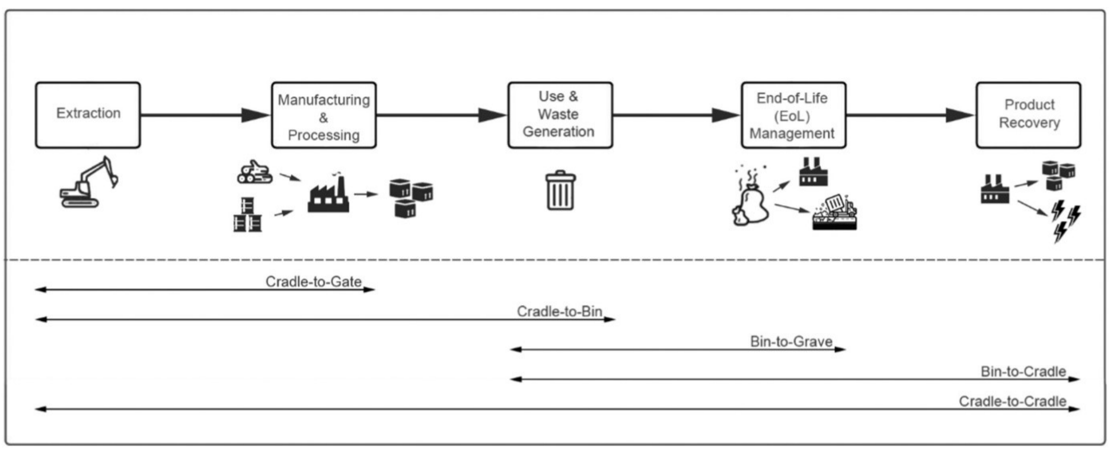

Figure 5 System Boundaries for Life Cycle Assessment

Studies on municipal solid waste often use a "bin to cradle" approach, which ignores trash generation and disposal. Thus, "gate," which takes into consideration when an item truly becomes garbage and is disposed, replaces "cradle," which takes into account extraction, manufacture, and utilisation. A flowchart with inputs and outputs is a useful representation of the system boundaries. Most MSW studies treat waste collection and transportation as system boundaries because of the assumptions and inputs they require, but these boundaries can be disregarded if they are constant across all scenarios. Additionally, most research also takes secondary outputs in the system's margins into account. Negative effects include residues that must be transported and disposed of in landfills, whereas positive effects include, for example, the replacement of traditional goods.

2.6.4. Life Cycle Inventory

This part of the LCA process is concerned with gathering the necessary information to carry out the LCA analysis. According to the defined objectives and parameters, the obtained data must be precise, comprehensive, and verified before being used. As a consequence, an inventory is built, which helps to define the system more precisely. It is at this stage that any remaining data needs that have emerged may be gathered and integrated into the inventory (ISO 14044, 2006).

Input parameters connected to trash should be gathered more carefully for LCA studies involving MSW, since they are the most crucial (Iqbal et al., 2020).

2.6.5. Ecoinvent Database

The use of the Ecoinvent Database facilitates users in acquiring a more profound comprehension of the environmental repercussions associated with their respective goods and services. The collection encompasses a wide array of areas at both the global and regional levels. The database now has over 18,000 activities, often known as datasets, that simulate human behaviours or processes. The Ecoinvent datasets encompass data pertaining to the industrial or agricultural processes they represent. These datasets quantify the extraction of natural resources from the environment, the discharge of emissions into water, soil, and air, the requisition of products from other processes (such as electricity), and, naturally, the generation of products, by-products, and waste materials (Ecoinvent).

2.6.6. Life Cycle Impact Assessment

Impact assessment is performed to ensure that the LCA research produces findings that are in line with the intended purpose and scope. Classification and characterisation are used for this purpose. Characterization is the outcome of classification based on category indicators, whereas classification is the process by which LCI findings are assigned to impact categories (ISO 14044, 2006). Environmental impacts may be broken down into many groups depending on the kind of emissions they produce. For instance, the greenhouse gases that cause global warming provide the basis of the "Climate Change" effect category. The table below summarises the various types of Impact and the corresponding indicators (Hillege, 2020).

Table 2 Impact Categories and Indicators.

Impact Category	**Impact Indicator**
Climate Change	The contribution of greenhouse gas emissions to global warming
Ozone Depletion	Stratospheric ozone-depleting emissions
Acidification	Acidification of soil and water due to nitrogen oxides and sulphur oxides emissions
Eutrophication, fresh water	Nutrient enrichment of fresh water habitats as a result of nitrogen and phosphorus emissions
Eutrophication, marine	Nitrogenous compound emissions, which boost marine ecosystems' nutrient levels.
Eutrophication, terrestrial	Releases of nitrogen molecules that improve soil fertility are a major contributor to global warming.
Photochemical Ozone Formation	Smog-inducing emissions: sunlight-catalyzed photochemical ozone in the troposphere
Depletion of Abiotic Resources, minerals and metals	Depletion of natural, non-fossil resources as a result of emissions
Depletion of Abiotic Resources, fossil fuels	Pollutants released into the air that deplete supplies of fossil fuels
Freshwater Ecotoxicity	The release of poisonous chemicals that harm aquatic life in freshwater environments
Particulate Matter Emission	Disease-inducing particulate matter emissions
Water Use	Reflects the percentage of total water use
Land Use	Reflects variations in soil quality

Midpoint and endpoint indications are often utilised to better comprehend the LCIA findings. According to this method, three final indicators (Table 3) are derived from the effect categories (midpoint indicators) (Bare et al., 2000).

Table 3 Midpoint Indicators and Endpoint Indicators

Midpoint indicator	**Endpoint Indicator**
Climate Change	Damage to human health
Water Use	
Ozone Formation	
Ozone Depletion	
Particulate Matter Emission	
Terrestrial Acidification	Damage to ecosystems
Freshwater Ecotoxicity	
Land Use	
Mineral Resource Scarcity	Damage to resource availability
Fossil Fuels Scarcity	

Different sets of impact categories and indicators derived using various models are used by the various LCIA techniques included in the various software packages. General LCA studies have made heavy use of SimaPro and GaBi, whereas waste management-focused studies have made use of EASETECH, SIWMS, WRATE, and IWM. What kind of software a specialist uses is entirely up to them.

The characterisation approach is used to transform inventory data into distinct effect categories. The elucidation of various approaches and their manifestation may be further expounded upon in relation to their level of contemporaneity. The two most reliable methodologies, namely CML and IPCC, were established before to the 21st century and have since undergone regular updates to ensure their ongoing relevance and accuracy. Both the Eco-Indicator and EDIP methodologies were created over a comparable timeframe. However, there is a noticeable decline in the use of subjects relating to solid waste management (SWM). The techniques known as ILCD, ReCiPe, and USEtox have emerged as notable developments in the field since 2008. CML and TRACI are examples of midpoint-based methods, while Eco-Indicator and EPS2000 represent endpoint-based approaches. The ReCiPe methodology serves as an illustrative instance of using a balanced midpoint/endpoint strategy, which has been extensively used in previous research investigations (Mulya et al., 2022).

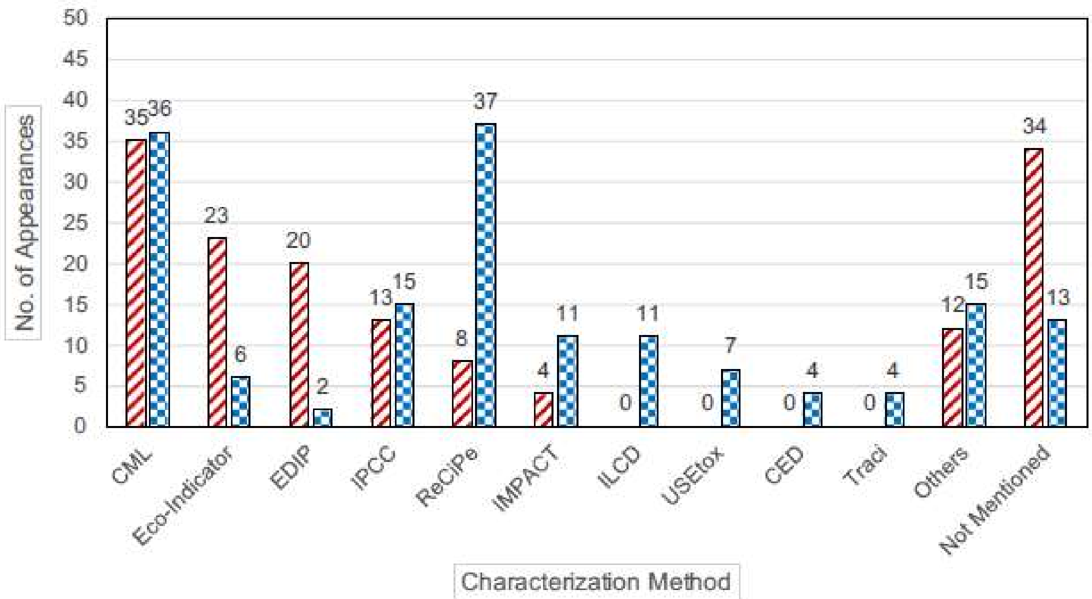

Figure 6 Number of Appearance of Characterisation Models

2.6.7. Sensitivity Analysis

Sensitivity analysis (SA) is used to determine if any assumptions made have a significant impact on the outcomes of the LCI, and if so, to identify which assumption has the most effect. Therefore, the aforementioned study by Khandelwal et al. (2018) offers valuable insights on the reliability of the LCI findings, as well as identifying areas that need more accurate data in order to enhance the inventory.

$$S.R = \left(\frac{\Delta\ result}{initial\ result}\right) \Big/ \left(\frac{\Delta\ parameter}{initial\ parameter}\right)$$

The sensitivity ratio (SR) is a measure used to quantify the sensitivity of results to changes in a single parameter. Effect categories with SRs over 0.8 are considered considerable, whereas those with SRs below 0.2 are thought less important, as stated by Liikanen et al. (2017).

2.7. Previous Studies in LCA of MSW

To determine the most effective strategy for long-term energy recovery and waste management, several studies have done LCA on a wide range of wastes, using a wide variety of treatment scenarios and waste treatment combination choices (Arena et al., 2015). The environmental impact of gasification and incineration for handling municipal solid waste was studied by

Arena et al. in 2015. The results show that for the European composition of residual MSW, incineration results in a less environmental impact than gasification does across the board.

An LCA of four WtE technology facilities (i.e., gasification-melting, gasification, incineration, and pyrolysis) for MSW treatment was also examined by Dong et al. (2018a). Compared to pyrolysis and gasification, the incineration plant performed better. The increasing acceptance of incineration may be attributed to its capacity to effectively manage fly and bottom ash and to make use of combined heat and power (CHP). The significance of energy efficiency in thermal technology is shown by this study's SA.

An LCA of municipal solid waste incineration and gasification in China, France, and Finland were compared by Dong et al. (2018a) in their own study. Results showed that across all seven impact categories examined, gasifying MSW in Finland resulted in a less environmental footprint than burning of MSW in France and China. There are less negative environmental repercussions from burning municipal solid waste in France than there are in China because French MSW has a higher calorific value. The contrast between gasification and incineration as waste disposal technologies exemplifies how regional choices about the environment may vary widely. Compared to thermal WtE technologies and the AD technique, landfilling has been observed to emit greater greenhouse gases (Zhou et al., 2018).

When comparing consequences, such as greenhouse gas emissions, Demetrious et al. (2018) showed that landfilling was superior than gasification and incinerator pyrolysis. There is a connection between environmental results and factors including waste type, resource recovery efficiency, and the kind of energy used in a given location. There is a dearth of published research on the issue of the environmental impact of MSW management in Australia, despite the fact that life cycle assessments (LCAs) of MSW have been performed in other countries.

This study used LCA comparisons to evaluate the potential of municipal solid waste (MSW) in the Australian state of New South Wales (NSW) through different scenarios of combining different WtE technologies and recycling for material recovery, energy manufacture, and their burdens on the environment across a variety of impact categories.

Environmental impacts were calculated by ranking the potential scenarios for power generation and then diving further into the most promising ones with respect to energy conversion and plastic recycling rates. When WtE waste was eventually recycled, the environmental effects could be assessed. New South Wales (NSW), Australia, might benefit from greater resource recovery and less environmental consequences if this study's findings are implemented.

2.8. Tools for LCA of MSW

Data collection, organisation, analysis, modelling of waste management systems, and evaluation of emissions and their environmental impacts are all aided by the use of computer-based technology. Cleary (2009) states that LCA relies heavily on process-based computer models. All of the model's parameters may be multiplied using the datasets included in these models. Regional, national, industry, agricultural, and consultant-specific LCA databases are available from a variety of sources. Ecoinvent, Needs, ELCD, and others are all examples of sites in this category. The MSWM field makes use of a number of different life cycle assessment (LCA) models, including SimaPro, GaBi, EASETECH (Environmental Assessment System for Environmental TECHnologies), previously known as EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies), IWM, and others. Figure 8 shows that almost 64% of the research employed LCA models to improve MSWM system efficiency and evaluate the environmental consequences and benefits of the resulting changes. Data analysis indicated that SimaPro was utilised in 44 experiments, GaBi in 25, EASETECH in 16, IWM in 7, and other LCA models were employed in 4. Several LCA models were utilised for the calculations in two distinct studies (Burnley et al., 2015; Kulczycka et al., 2015). Fifty-six of the total number of papers analysed lacked detail about the LCA model's use. It was noted, however, that the LCA calculations in these research were done using equations. While life cycle assessment (LCA) models are not required, their usage simplifies and speeds up otherwise laborious computations. Multiple aspects determine a model's usefulness, including price, accessibility, language, research goal, and user choice (Yadav and Samadder, 2018).

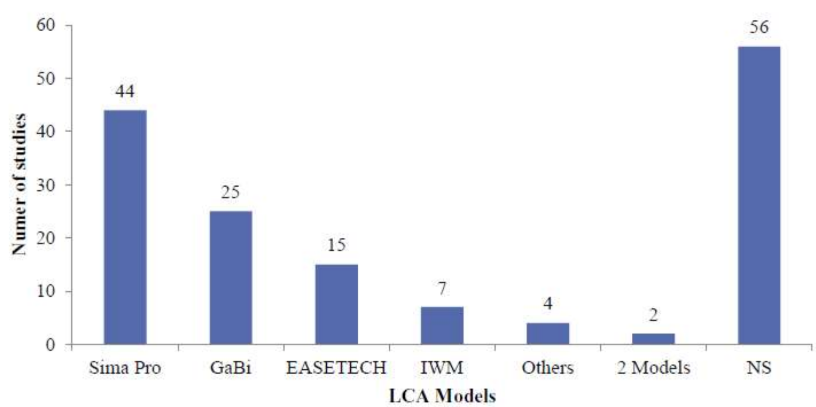

Figure 7 Number of Studies for Different LCA Models

Chapter 3

3. METHODOLOGY

3.1. Study Area

Peshawar is situated in the north-west of the country and is the sixth largest city in Pakistan with a population of over 4.3 million (Census 2017) and has 93 union councils. It is situated at an altitude of 331m above the mean sea level. The annual precipitation for the year 2021 was recorded as 296.60 mm (Pakistan Metrological Department). The city generates 967 tons of waste per day with an average of 2.24 kg/capita/day. Water and Sanitation Services Company, Peshawar (WSSP), a municipal authority responsible for providing waste management services in Peshawar, collects 55% of the total waste generated and dumped in an open dumping site, 26 km away from the city centre, available at Shamshatoo, Peshawar. The open dumping site has an overall area of 414,297 m^2 out of which 60% has been utilised. The present study covers urban area of the city which comes under the jurisdiction of WSSP.

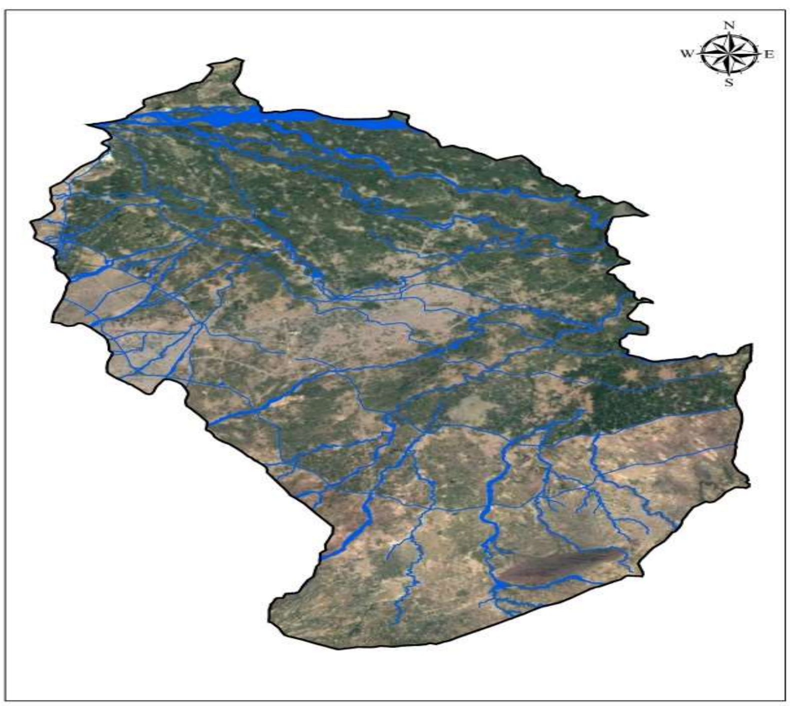

Figure 8 Map of District Peshawar

3.2. Data Collection

The secondary data has been obtained from WSSP for the year 2021-22. The percentage composition of MSW in urban area of Peshawar is given below in Table 4. % Recovery from the scavengers has been taken from the study (Gohar et al., 2022) conducted for Peshawar.

Table 4 Secondary Data for MSW in Peshawar

Waste Category	Waste Type	% Waste Generation	% Recovery through Scavengers	% Remaining
Recyclables	Metal Iron	1.49	1.40	0.09
	Aluminium	0.72	0.25	0.47
	Glass	2.36	0.98	1.38
Reusable	Building Material/Sand	3.27	1.14	2.13
Combustible	Paper / Cardboard	10.73	2.97	7.76
	Wood	4.10	2.67	1.43
	Textile	3.53	0.22	3.31
Biodegradable	Food	48.82	1.95	46.87
Plastics	Plastics	12.34	0.60	11.74
Others	Diapers	4.79	-	4.79
	Miscellaneous	7.85	-	7.85
Total		**100**	**12.18**	**87.82**

3.3. Life Cycle Assessment

3.3.1. Goal and Scope

The purpose of this research was to examine the environmental effects of various garbage management strategies i.e., open dumping, and three other waste management alternatives / treatment facilities i.e., sanitary landfill, incineration and anaerobic digestion, has been proposed. The life cycle scope has been considered as "Gate to Cradle" which includes the MSW to be treated through treatment facilities, co-products to be re-used (avoided products) and later final disposal.

It has been assumed that all the treatment facilities are available at the location of unsanitary landfill. Therefore, the emissions from collection and transport would be same for all the treatment facilities, hence not considered.

Furthermore, the major portion of recyclables are recovered through scavengers and a minute amount has remained, it has been assumed that the minute amount of recyclables are also recovered through scavenger. In the case of building material/sand which is reusable, thus assumed to be reused and not entering into the system. The plastic waste was assumed to be totally combustible with no recyclable component in it.

The functional unit has been selected as 1 metric tonne of MSW.

This study was carried out using SimaPro version 9.3.0.3 having Ecoinvent database considering long term emissions. The long-term emissions refer to the emissions occur over large time frames of sustainability up to 150 years.

3.3.2. Scenarios

There are five potential futures for MSW management in Peshawar beyond the current status quo.

System Boundary: The delineation of the system boundary establishes the specific process that is to be included within the LCI model. As shown in the Figure 10, the system border encompasses the raw materials, namely minerals and fossil fuels, that are extracted, as well as the energy necessary for their extraction and the operation of waste treatment facilities. The emissions to the air, water, and soil are the output generated by the system boundary. The co-products, including biogas, leachate, and power, that are generated during the treatment of MSW via landfilling, incineration, and anaerobic digestion, exit the system boundary as avoided products. An avoided product refers to a commodity that is used in the production of other products and services.

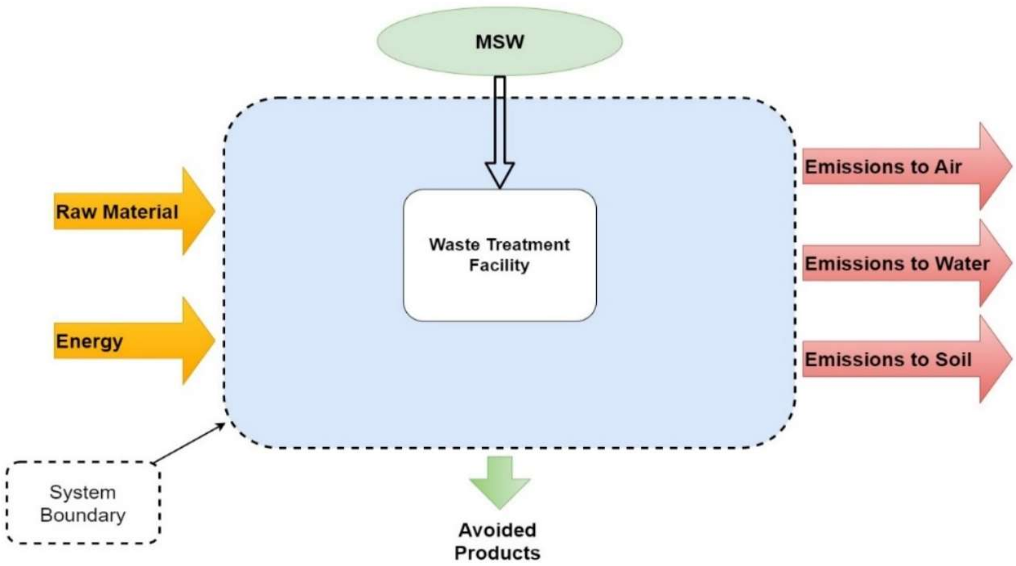

Figure 9 System Boundary for LCA

The scenarios along with their system boundaries are discussed below:

3.3.2.1. Scenario 1 (Sc1) – Open Dumping (Baseline Scenario)

This scenario aligns with current municipal solid waste management practices, in which the collected MSW is openly dumped. Following the dumping process, a tractor equipped with blades is used to achieve a uniform level of the waste material. This operation necessitates the consumption of about 6 litres of diesel fuel every tonne of MSW.

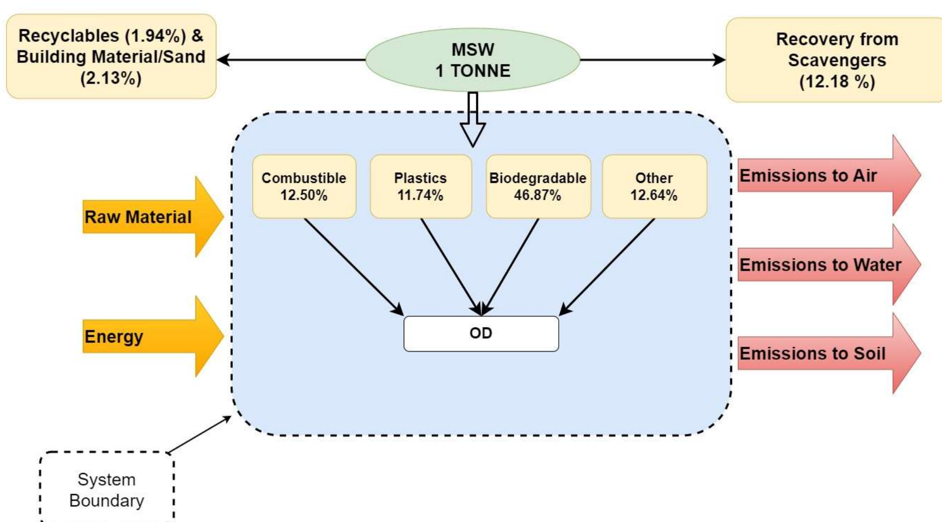

Figure 10 System Boundary of Sc1

3.3.2.2. Scenario 2 (Sc2) – Landfill

This scenario assumes that all the accumulated MSW is transported to a sanitary landfill that incorporates a leachate and biogas collecting system, as seen in Figure 12. The leachate is left untreated, thus emits emissions to the environment. Additionally, the landfill gas, containing 75% energy, is deemed suitable for use as a natural gas resource to generate heat.

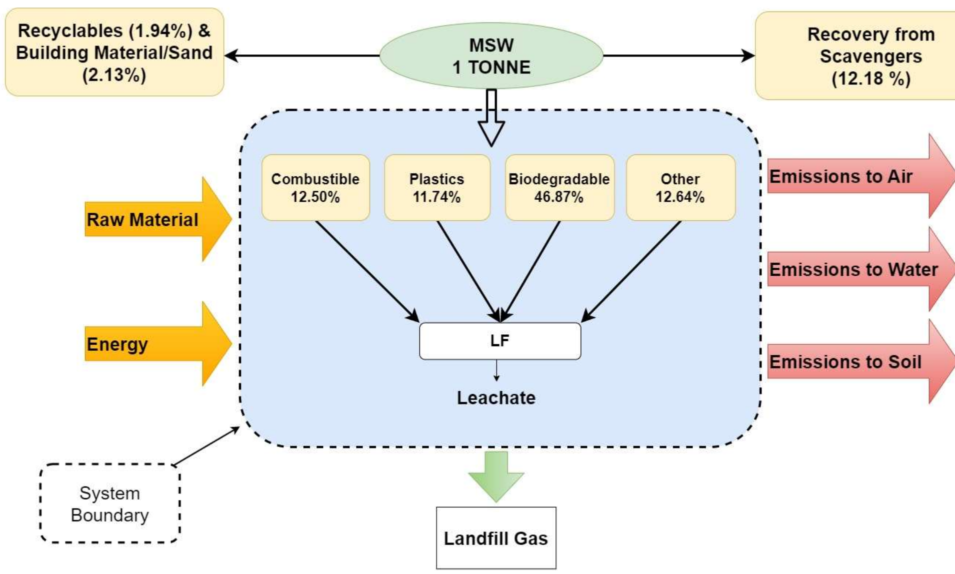

Figure 11 System Boundary of Sc2

3.3.2.3. Scenario 3 (Sc3) – Incineration and Landfill

This scenario encompasses both incineration and a sanitary landfill, whereby combustible materials and plastics are sent to incineration, while biodegradable materials and other items are directed to the landfill, as seen in Figure 13. The chosen technology for the incinerator is the grate incinerator equipped with an electrostatic precipitator for the capture of fly ash. The byproducts of incineration, namely bottom ash and fly ash, are disposed of in landfills, whereas the production of power from incineration is seen as a product that is avoided.

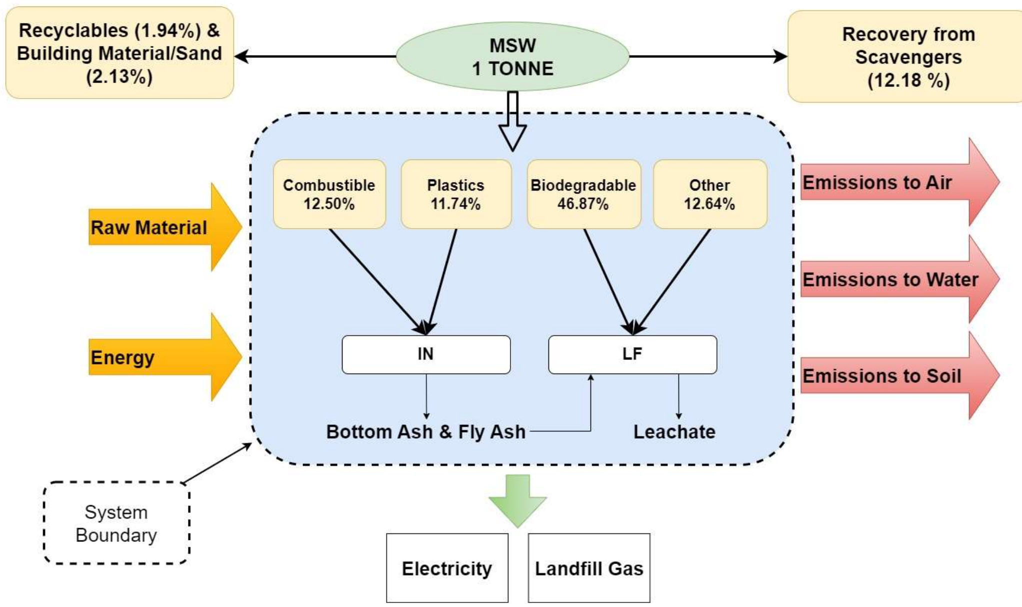

Figure 12 System Boundary of Sc3

3.3.2.4. Scenario 4 (Sc4) – Anaerobic Digestion and Landfill

As shown in Figure 14, this scenario involves the use of both anaerobic digestion and a sanitary landfill. Specifically, the biodegradable waste undergoes anaerobic digestion, while plastics, combustible and others are sent to the landfill. The chosen method for the anaerobic digester is "thermophile, single stage digestion with post composting." This technology assumes that 40% of the total biodegradable waste is dry mass by default. In this context, the sludge digester is designated for disposal in a landfill, whilst the biogas produced by anaerobic digestion is being considered for utilisation as a renewable resource of natural gas for heating purposes.

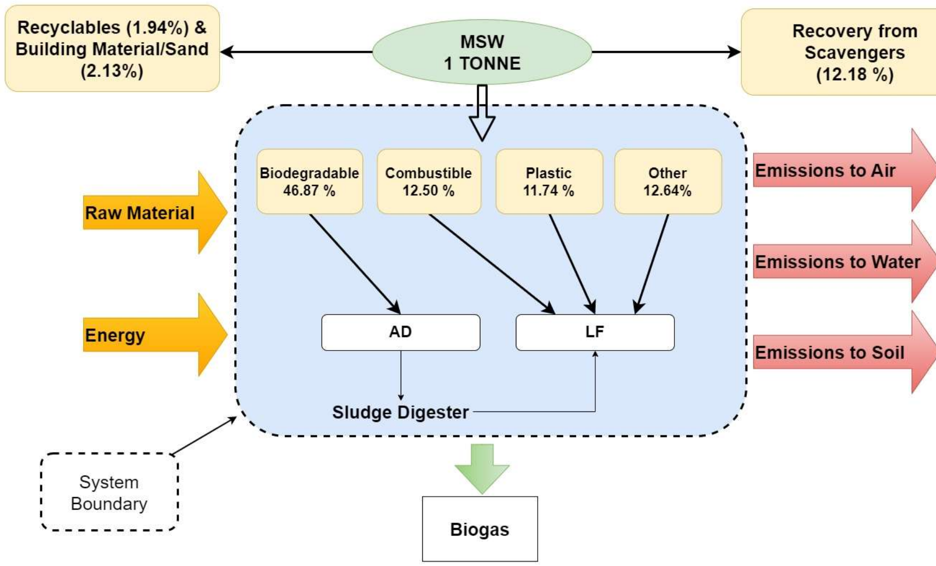

Figure 13 System Boundary of Sc4

3.3.2.5. Scenario 5 (Sc5) – Anaerobic Digestion, Incineration and Landfill

The proposed methodology involves the use of an integrated strategy, whereby combustible materials and plastics are subjected to incineration, biodegradable substances are processed through anaerobic digestion, and other waste materials are appropriately disposed of in a sanitary landfill as shown in Figure 15.

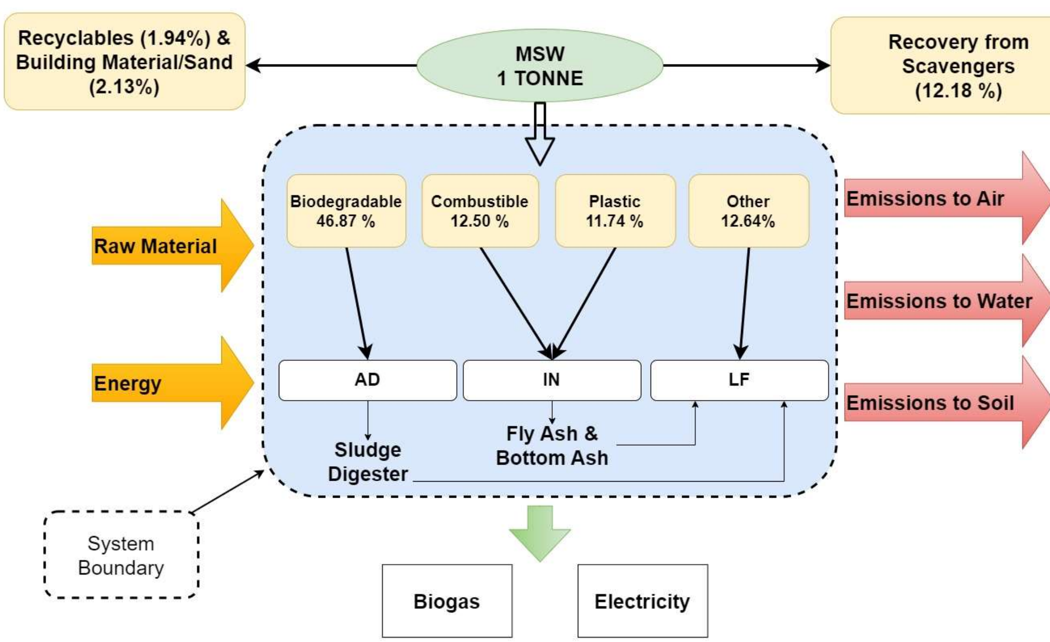

Figure 14 System Boundary of Sc5

3.3.3. Life Cycle Inventory

Foreground data, i.e., emissions related with the MSW treatment facilities, and background data, i.e., figures for fuel consumption and co-products generation, were collected for the LCI from the literature and the Ecoinvent database.

Open Dumping:

A tractor equipped with blades consumes 6 litres of diesel fuel per tonne of MSW in order to do the task of levelling the openly dumped MSW at the open dumping site located in Peshawar, managed by the WSSP (Source: WSSP).

Landfill: According to Khandewal et al. (2019), a compactor consumes 3 litres of diesel fuel in order to compress 1 tonne of MSW inside a landfill. According to Sohoo et al. (2022), a study conducted for Karachi, Pakistan, the landfill gas generation is 187 cubic metres per metric tonne of waste. This research examines the utilisation of landfill gas, a byproduct that is often discarded, for household heating purposes. The volume of landfill gas considered in this study is 140 m^3, with an assumed efficiency of 75%. The annual volume of leachate generated from the landfill, as determined by the methodology used by Ibrahim et al. (2017), amounts to 11,036 cubic metres per year.

$$V = 0.15 \times R \times A$$

V: Volume of leachate (m^3 per year); R: Annual Rainfall (m); A: Surface area of the landfill (m^2)

Incineration: The byproducts resulting from the process of incineration include bottom ash and fly ash, both of which are disposed of in landfill. According to the Ecoinvent database, the default value for the amount of these residues produced is 0.6kg per kg of waste incinerated. Additionally, the incineration process generates energy at a rate of 0.385 kWh per kilogramme of waste burnt.

Anaerobic Digestion: The remaining material that is produced as a consequence of anaerobic digestion is often known as sludge digester, and it is typically disposed of in landfills. Based on data from the Ecoinvent database, the default value for the sludge digester yield per kilogramme of biodegradable waste is 0.6 kg/kg. Furthermore, it is worth noting that the Ecoinvent database assigns a default value of biogas generation as 0.1 m^3/kg of waste. This biogas, derived from biodegradable trash, is used as a source of natural gas for heating applications.

3.3.4. Life Cycle Impact Assessment

To evaluate the environmental burdens and benefits, the impact assessment was carried out using the LCA software SimaPro version 9.3.0.3 and ReCiPe 2016 method with midpoint impact categories and endpoint damage assessment.

3.3.5. Sensitivity Analysis

A certain degree of uncertainty has been recognised about plastic waste, since it was originally believed to be completely combustible with no recyclable constituents. The potential for the recyclability of plastic waste is constantly seen. In order to evaluate the effects on the results of endpoint damage assessment categories, an SA was performed on plastic waste across several scenarios.

It has been assumed that a significant proportion, around 40%, of plastic waste has the capacity for recycling and thereafter undergoes processing at a Material Recovery Facility (MRF). In contrast, the remaining 60% of plastic waste is classified as combustible and is subjected to incineration. The approach used for conducting the SA involves the consideration of four distinct scenarios. Each scenario assumes an incremental increase of 10% in the plastic waste being processed by the MRF.

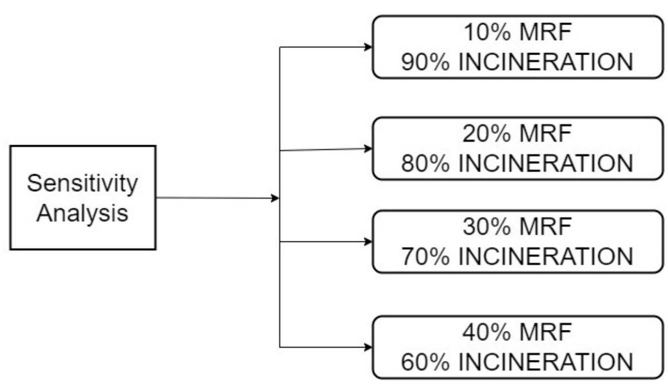

Figure 15 Methodology of Sensitivity Analysis for Plastic Waste

Chapter 4

4. RESULTS AND DISCUSSION

4.1. Midpoint Approach

To get a full view of a process's environmental evaluation, the ReCiPe approach employs indications at the procedure's midpoint. Table 5 displays the interpretations of each impact for the present LCA analysis:

Table 5 Results of Midpoint Impact Categories

Mid Point Impact Category	Unit	Sc 1 (OD)	Sc 2 (LF)	Sc 3 (LF+IN)	Sc 4 (LF+AD)	Sc 5 (LF+IN+AD)
Global Warming	kg CO_2 eq	1027.73743	730.03694	627.60909	220.28642	117.85857
Stratospheric Ozone Depletion	kg CFC-11 eq	7.6309E-05	4.0986E-05	-3.4377E-05	3.4377E-05	-6.8754E-05
Ozone Formation,	kg NOx eq	0.03043218	0.0178139	-0.00263001	-0.02893369	-0.049377603
Fine Particulate Matter Formation	kg $PM_{2.5}$ eq	0.0596101	0.01349527	-0.01439086	0.0058022	-0.022083928
Terrestrial Acidification	kg SO_2 eq	0.31640966	0.21718172	0.17043505	0.013193806	-0.033552866
Freshwater Eutrophication	kg P eq	17.5896698	43.2535187	39.45966925	7.305199633	3.511350125
Freshwater Ecotoxicity	kg 1,4-DCB	9.43987257	5.66392354	3.775949027	2.831961771	2.333667655
Land Use	m^2	0.04481294	0.0071947	-0.04526597	-0.13202029	-0.184480952
Mineral Resource Scarcity	kg Cu eq	2.80170586	1.03563074	-0.18837256	-0.04941809	-1.199294228
Fossil Resource Scarcity	kg oil eq	0.01534263	0.14758845	0.270705097	0.238857439	0.402360928
Water Consumption	m^3	0.01534263	0.14758845	0.270705097	0.238857439	0.402360928

4.1.1. Global Warming

The effect of climate change may be measured with the help of the characterization factor. Measured in comparison to the radiative forcing caused by CO_2 over a certain time frame, a greenhouse gas's (GHG) extra radiative forcing is expressed as its Global Warming Potential (GWP). The increasing concentration of GHGs in Earth's atmosphere is blamed for amplifying radiative forcing, which in turn is responsible for the observed increase in global average temperature. Human health and ecosystems both suffer as a result of the warming of the planet. Carbon dioxide equivalents per kilogramme of greenhouse gas (CO_2 eq/kg GHG) serve as the standard unit of measurement for GWP (Huijbregts et al. (2016)).

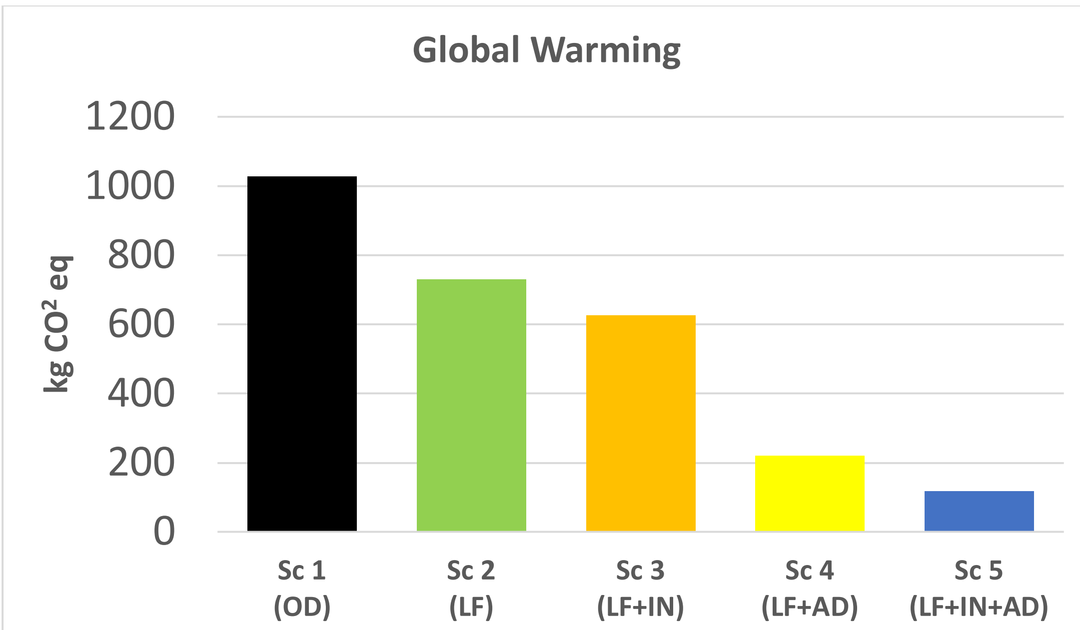

Figure 16 Result of GWP

Discussion: It can be seen from the Table 5 and Figure 16 that the greatest impact on GWP results from Sc1 due to GHGs being released from the waste in the environment. Sc2 also contributes to the GWP. The primary cause of this phenomenon may be primarily ascribed to the emission of CO_2 resulting from the routine activities of compacting waste, as well as the generation of biogenic methane gas at the landfill site. In comparison, Sc1 contributes more than Sc2 in terms of GWP. Sc3, Sc4 and Sc5 resulted in negative emissions which shows that reducing the amount for landfilling can reduce the GHGs emissions. Here, Sc5 showed less negative impact on the environment because only 12.64% MSW is disposed of in the landfill, thus reducing the daily operations of compacting and methane gas production at the landfill.

4.1.2. Stratospheric Ozone Depletion

The release of Ozone Depleting Substances, namely those belonging to the chlorine and bromine group, is responsible for the escalation in UVB radiation levels. The release of these pollutants has the effect of diminishing the integrity of the stratospheric ozone layer, so facilitating the direct penetration of UVB radiation onto the Earth's surface. This occurrence poses a significant threat to human well-being, primarily by elevating the risk of skin cancer and cataract development. The metric used to quantify the ozone depleting potential of a material, relative to CFC-11, over a certain time period, is referred to as the ozone depleting potential. The unit of measurement for this quantity is kilogrammes of CFC-11 equivalent, as stated by Huijbregts et al. (2016).

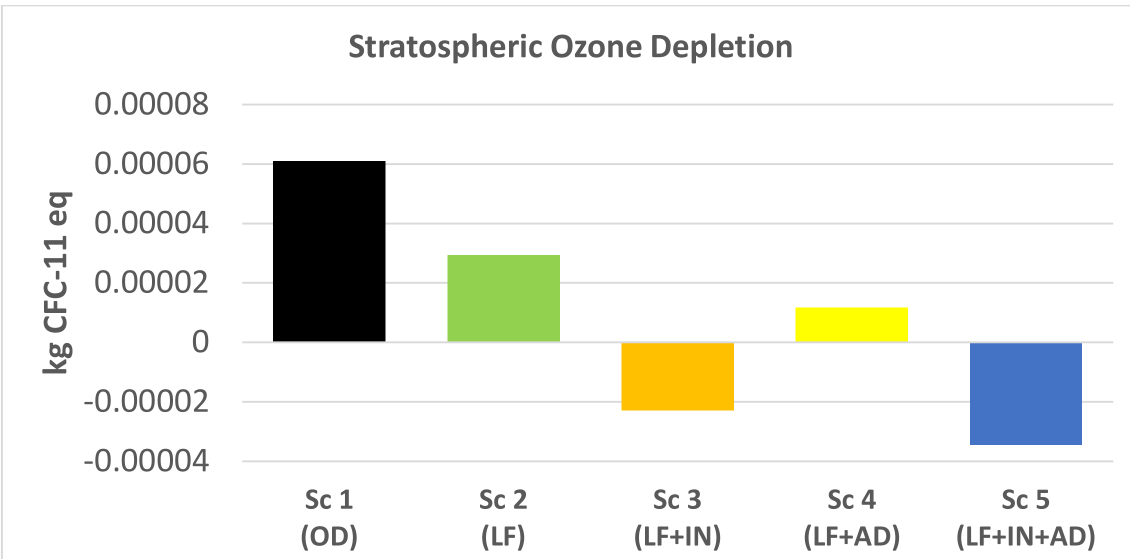

Figure 17 Result of Stratospheric Ozone Depletion

Discussion: As shown in the Table 5 and Figure 17, the significant contributor towards stratospheric ozone depletion is Sc1 followed by Sc2. The specific cause is the emission of CFCs resulting from the disposal of plastic trash, which leads to rapid ozone depletion. Additionally, the absence of a cover on Sc1 allows ultraviolet (UV) light to directly impact the plastic materials, resulting in the release of CFCs into the surrounding environment. In comparison, a landfill has cover, and does not permit open burning therefore saves does not contribute much towards this category. However, the small portion of contribution might result from the CFCs being emitted before the cover is placed on the landfill layer. Sc3 resulted in negative emissions because the plastic waste is incinerated with an air pollution control system and ozone depleting substance are not released. Sc4 shows positive emissions due to absence of incineration technology. Sc5 which possesses an incineration technology for plastic waste showed negative emissions. In comparison, Sc5 is better than the other scenarios.

4.1.3. Fine Particulate Matter Formation

Particles of a size of less than 2.5 nm are considered fine particulate matter, and they include a wide variety of organic and inorganic substances that might be harmful to human health if breathed in. Secondary PM2.5 particles are formed when sulphur dioxide, ammonia, and nitrogen oxides are present in the air. Potential Fine Particulate Matter (PM2.5) generation can be evaluated by measuring how the local concentration of PM2.5 responds to changes in the local concentration of its precursors, such as Sulphur Dioxide, Ammonia, and Nitrogen Oxides (Huijbregts et al., 2016). PM2.5-eq per kilogramme is the unit of measurement for this variable.

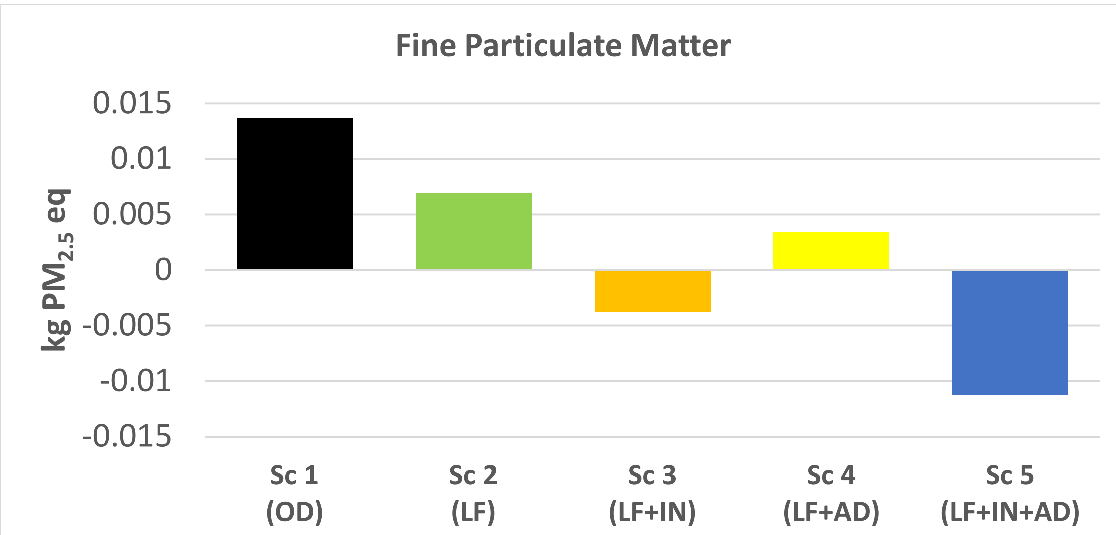

Figure 18 Results of Fine Particulate Matter

Discussion: The significant contributor towards fine particulate matter formation is Sc1 followed by Sc2. The particular reason is the release of aerosols from the daily operational activities on open dumping and landfilling site. The precursors of $PM_{2.5}$, Sulphur dioxide, ammonia and nitrogen, are being release when the machineries are used for leveling the dumped waste on open dumping site or compacting the waste in the landfill. Sc3 resulted in negative emissions because the incinerator operates with an air pollution control system and the proportion of waste for landfill is reduced. Sc4 shows positive emissions due to absence of incineration technology. Sc5 which possesses an incineration technology with an air pollution control system and requires limited activities for landfill as less MSW is disposed of in it. In comparison, Sc-5 is better than the other scenarios as shown in the Table 5 and Figure 18.

4.1.4. Ozone Formation

Human health has been found to be negatively impacted by ozone's presence in the Earth's atmosphere, notably in the respiratory system. Airway inflammation, lung damage, and an increased chance of developing respiratory illnesses like asthma have all been linked to ozone exposure. Plants are also negatively impacted, with less growth and fewer seeds produced as a consequence. It is the photochemical interaction between nitrogen oxides (NOx) and non-methane volatile organic compounds (NMVOCs) that contributes to the buildup of ozone in the atmosphere during the warmer months. Nitrogen oxides (NOx) and other non-methane volatile organic compounds (NMVOCs) in the atmosphere are measured for their ozone-generating capability and their impact on human and environmental health. NOx-equivalents per kilogramme is the unit of measure for this variable. Ozone formation's impact on human health and terrestrial ecosystems are two examples of the kind of effects that may be measured using the ReCiPe method (Huijbregts et al., 2016).

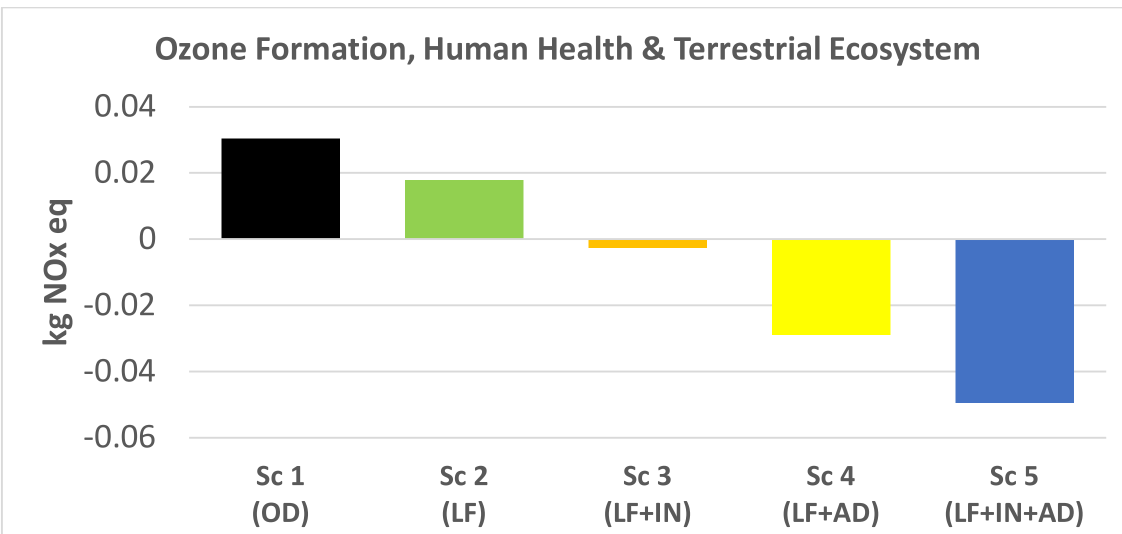

Figure 19 Results of Ozone Formation, Human Health & Terrestrial Ecosystem

Discussion: Table 5 and Figure 19 shows the Sc1 contributes most towards the formation of ozone because of the open dumping of MSW which is exposed to the sunlight. Further, the daily operations at the open dumping site i.e., using of machineries to level the dumped waste, contributes to formation of ozone in the day light. Sc2 performed better than Sc1 mainly due to cover over the landfill area and less machinery needed for daily operations. Sc3, Sc4 and Sc5 contributed positively towards the environment due to no entrance of NOx and NMVOCs in the atmosphere as the burden on the landfill is reduced by disposing of less MSW. In comparison, Sc5 is better due to negative emissions to the environment.

4.1.5. Terrestrial Acidification

Sulphates, nitrates, and phosphates possess the propensity to modify the soil's pH, hence potentially exerting detrimental effects on plant species. Every plant has a certain threshold of soil acidity that is considered optimal, and any deviations from this level may have significant repercussions on the overall health and well-being of the plant. The pollutants that have an impact on the acidity of soil include nitrogen oxides (NOx), ammonia (NH_3), and sulphur dioxide (SO_2). The assessment of terrestrial acidification involves quantifying the capacity of these particular species to modify the concentration of H^+ ions in soil subsequent to their deposition. The expression is denoted as kilogrammes of SO_2-equivalents per kilogramme, as stated by Huijbregts et al. (2016).

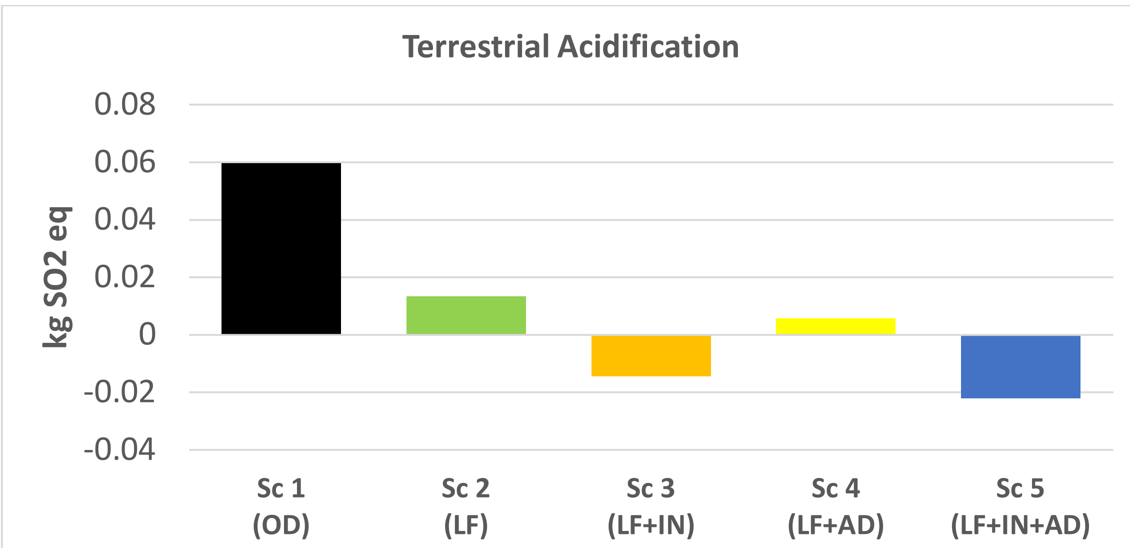

Figure 20 Results of Terrestrial Acidification

Discussion: Table 5 and Figure 20 shows the Sc1 has a disproportionately large effect in this area due to the soil's propensity for releasing sulphates and nitrates. However, landfills only contribute a fraction of this amount since they are lined and protected from soil infiltration by special barriers and liners. Sc3 showed negative emissions due to landfill with liner and the plastic waste which take years to decompose and affects the soil is incinerated. Sc4, in which, the combustible and plastic waste is landfilled, showed positive emissions. Sc5 being a combination of all the treatment technologies showed negative emissions as the combustible and plastic waste is incinerated and landfill is available with liner while biodegradable is treated through anaerobic digestion. In comparison, Sc5 stands better than the other.

4.1.6. Freshwater Eutrophication

Eutrophication occurs as a consequence of the increased concentrations of phosphorus and nitrogen in freshwater ecosystems. The phenomenon under consideration has extensive ramifications, including enhanced nutrient absorption by autotrophic organisms such as algae, as well as by heterotrophic animals like fish, eventually leading to species depletion. The assessment of phosphorus and nitrogen's capacity to induce eutrophication is conducted via the use of intricate models that ascertain the increase in eutrophication levels in freshwater systems, taking into account variables such as residence duration, advection, retention time, and other relevant parameters. The unit of measurement for this parameter is kilogrammes of phosphorus per kilogramme of fresh-water equivalents, as stated by Huijbregts et al. (2016).

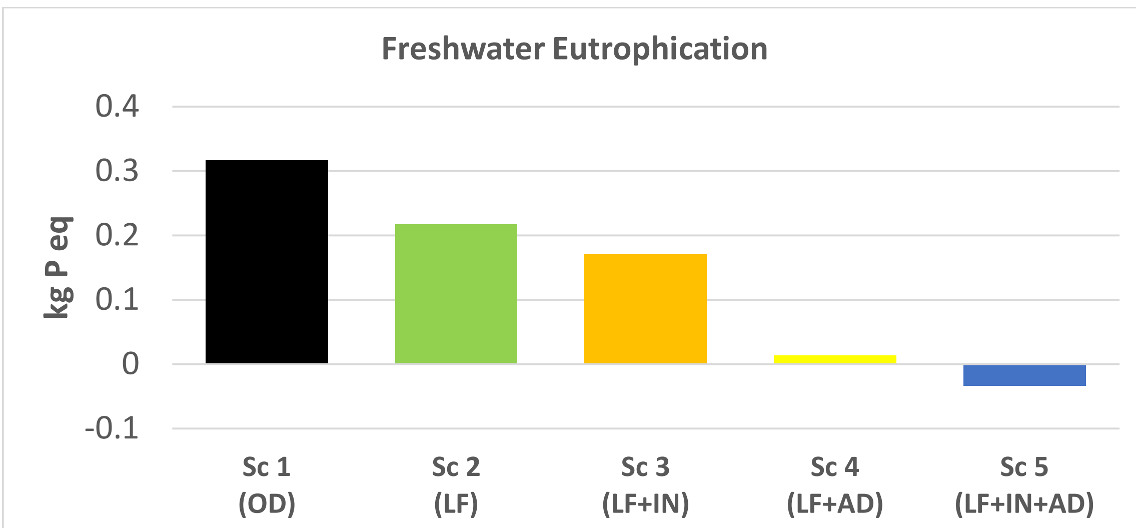

Figure 21 Results of Freshwater Eutrophication

Discussion: In this case, the most contribution results from Sc1 as shown in the Table 5 and Figure 21 due to Phosphorus is deposited in freshwater mostly as a consequence of leachate generation and run off caused by rainfall on the open dump site. when a consequence, eutrophication occurs when the freshwater's BOD and COD rise. Sc2 involves landfilled trash that is protected from precipitation so that less phosphorus is washed away. In Sc3, the biodegradable waste which is main contributor to leachate production is disposed of in the landfill, thus, possibility of deposition of phosphorus in the soil or waste through runoff from the rainfall on the landfill area. Sc4 which treats the biodegradable waste through anaerobic digestion and relieving the landfill from the production of leachate performed better than Sc1, Sc2 and Sc3. However, a combination of all technologies, Sc5, is better than the former scenarios as the leachate production from the landfill is of no account.

4.1.7. Freshwater Ecotoxicity

This study assesses the occurrence of several organisms that have the potential to pose toxicity risks to human health or the environment in the long term. The assessment is conducted by comparing the potential "toxicity" of the substance in question to that of 1,4-Dichlorobenzene. The unit of measurement for 1,4-DCB is kilogrammes, as stated by Huijbregts et al. in 2016.

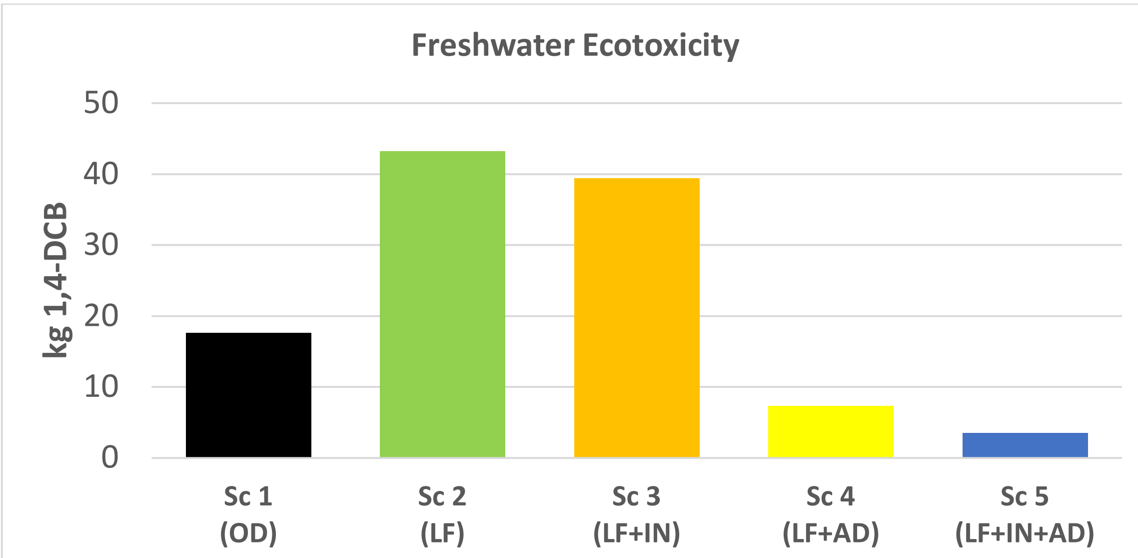

Figure 22 Results of Freshwater Ecotoxicity

Discussion: In this category, Sc2, on the basis of long-term emissions (150 years), showed maximum positive emissions. This is primarily due to the failure of liner in the landfill after 100 years. Upon failure of liner in the landfill, the leachate can affect the soil and water. Sc5 performed better than the other scenarios as the leachate production in the landfill is insignificant as shown in the Table 5 and Figure 22.

4.1.8. Water Consumption

This study assesses the implications of decreased freshwater supply. The decrease in availability of freshwater resources results in a corresponding decrease in the capacity for irrigation, hence contributing to the occurrence of hunger. The model assumes that the decrease in blue water resources, such as lakes and aquifers, would have a subsequent impact on green water resources, namely the moisture content of soil. This reduction in green water availability is expected to result in a decline in plant and vegetative growth. Furthermore, this phenomenon will also result in a decrease in the population of fish inhabiting freshwater ecosystems. The potential is assessed by a comparison of the water consumption to water extraction ratio. The unit of measurement used is cubic metres (m^3) (Huijbregts et al., 2016).

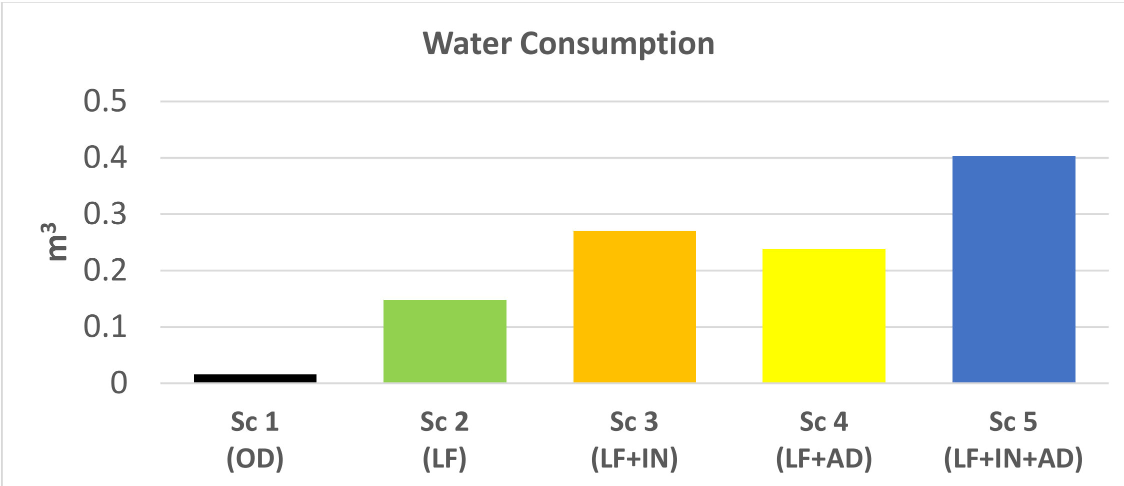

Figure 23 Results of Water Consumption

Discussion: In this case, Sc1 showed minimum positive emissions due to insignificant water usage. Sc2, Sc3, Sc4 and Sc5 showed higher positive emissions due to development of infrastructure which in which the consumption is more as shown in the Table 5 and Figure 23. Sc3 consumes more water due to availability of wet scrubbers in the incineration. Sc5 which possesses all three technologies consumes more water than other scenarios for the construction purposes. Sc1 being better in this category because the open dumping requires no infrastructure.

4.1.9. Land Use

This study quantifies the impact on habitat loss and soil disturbances induced by changes in land cover and intensified land use, leading to the extinction or destruction of species and ecosystems. The unit of measurement used in this study is square metres, as indicated by Huijbregts et al. (2016).

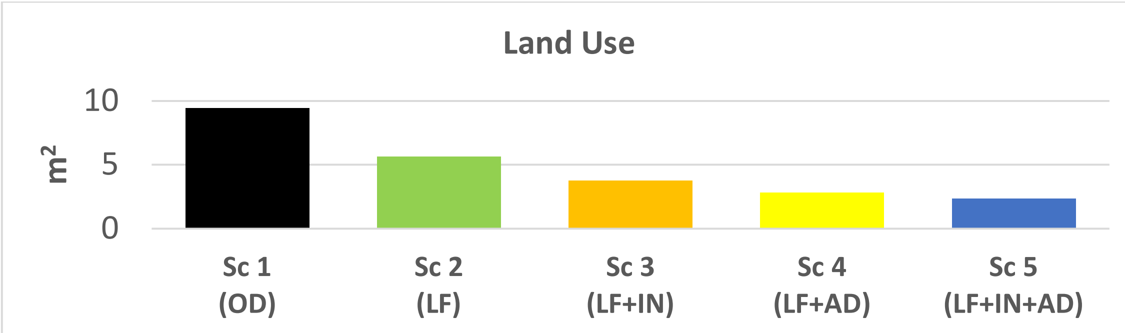

Figure 24 Results of Land Use

Discussion: Sc1 contributes the most to this impact category because the open dumping surface area is huge as no depth is involved. Similarly, involvement of depth in the landfill (Sc2) showed less negative impact than Sc1 because the surface area is reduced while the volume is increased. As shown in the Table 5 and Figure 24, the contributory factor is landfill as the other technologies requires less area than landfilling. Less waste diverted to landfill means less area required to construct the landfill. Sc5 which has very less waste diverted to landfill required less area, hence, better than the other scenarios.

4.1.10. Mineral Resource Scarcity

This metric quantifies the degree of scarcity arising from the exploitation of mineral resources that are globally extracted and used. Additionally, this phenomenon leads to a rise in the price of the mineral, as its availability diminishes gradually. The measurement of this variable is expressed in units of money, as stated by Huijbregts et al. (2016).

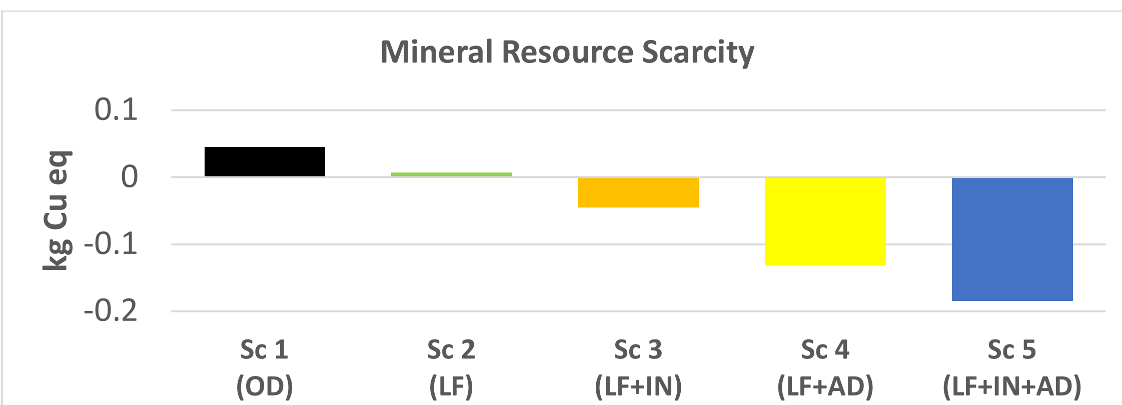

Figure 2 Results of Mineral Resource Scarcity

Discussion: Sc1 contributes the most due to no avoided product. Due to availability of avoided products in Sc2, Sc3, Sc4 and Sc5, the negative emissions have been obtained as shown in the Table 5 and Figure 25. Sc5 putting the positive impact on the environment as the avoided products from landfill, incinerator and anaerobic digestion is reused which reduces the need for mining resources in the production of avoided products somewhere else.

4.1.11. Fossil Resource Scarcity

This metric quantifies the degree of scarcity arising from the global use and utilisation of fossil fuels. For instance, in the event that the current oil reserves become exhausted, there will be a need to extract oil from the Arctic areas, resulting in increased costs and an elevated pace of oil production. The measurement of this variable is denoted in terms of monetary units, as indicated by Huijbregts et al. (2016).

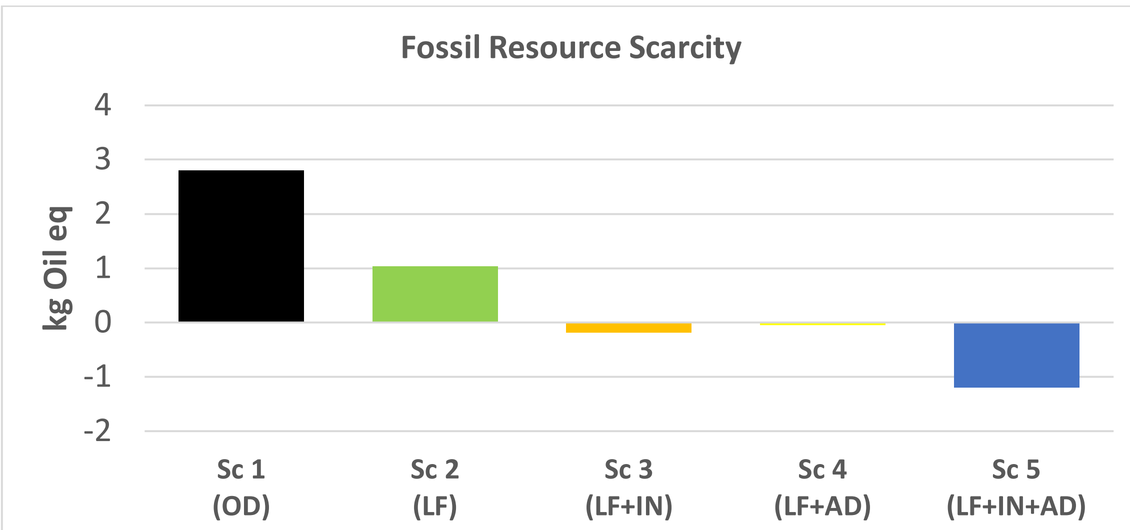

Figure 26 Results of Fossil Resource Scarcity

Discussion: Sc1 contributes towards the scarcity more due to use of machineries which uses fossil fuels followed by Sc2. The negative impact in Sc2 is minimised as the biogas has been used as an avoided product. Sc3, Sc4 and Sc5 have the positive impact in this category due to the avoided products from incinerator and anaerobic digestion. In comparison, Sc5 is better than the other scenarios as shown in the Table 5 and Figure 26.

4.2. Endpoint Approach

The damage assessment is the aggregate of the end point indicators, which are calculated by adding up the effects. These calculate a "single score" for evaluating three outcome indicators: human health, ecosystem health, and resource health. The latest LCA study's Damage Assessment, seen in Table 6, is explored in further detail below.

Table 6 Results of Endpoint Damage Categories

End Point Damage Category	Unit	Sc1 (OD)	Sc2 (LF)	Sc3 (LF+IN)	Sc4 (LF+AD)	Sc5 (LF+IN+AD)
Human Health	DALY	0.000105412	7.65676E-05	5.58301E-05	2.99198E-05	9.18237E-06
Ecosystems	species.yr	3.19796E-07	2.25054E-07	1.84826E-07	1.05772E-07	6.55447E-08
Resources	USD2013	0.556411049	0.406700782	0.288056825	-1.11597348	-1.23461742

4.2.1. Human Health

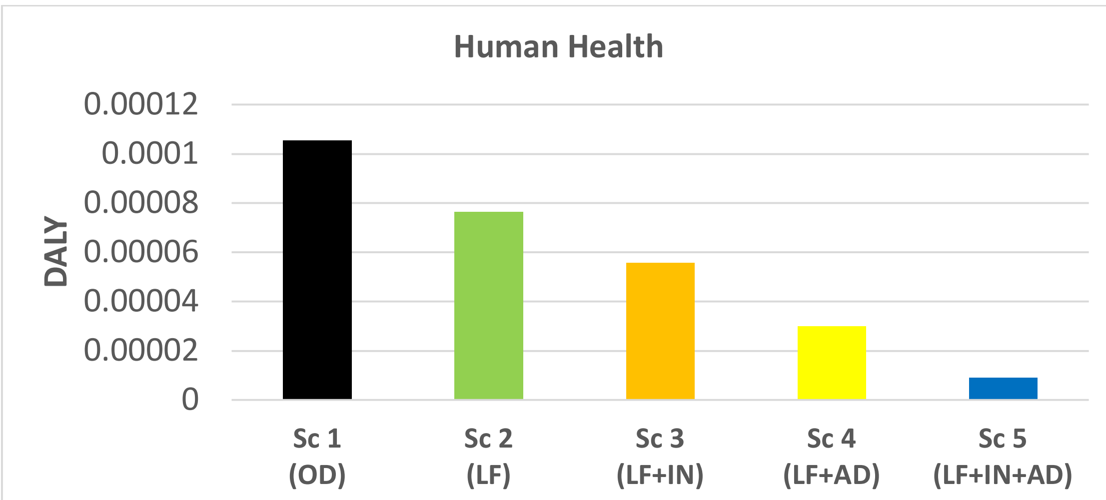

Figure 27 Results of Human Health

Discussion: Table 6 and Figure 27 reveal that Sc1 is the most dangerous to people, with Sc2 coming in second. All the average indicators have shown this as well. Sc4 is preferable to Sc3 because of the development of leachate, which occurs when landfilled biodegradable trash (around 47%) decomposes. A lack of leachate generation in Sc4's landfill is due to the use of anaerobic digestion on the same biodegradable trash. Sc5, which includes the use of all three therapeutic technologies, outperforms the other scenarios and causes the fewest number of DALYs (disability-adjusted life years) of human suffering due to disease or injury to be lost.

4.2.2. Ecosystems

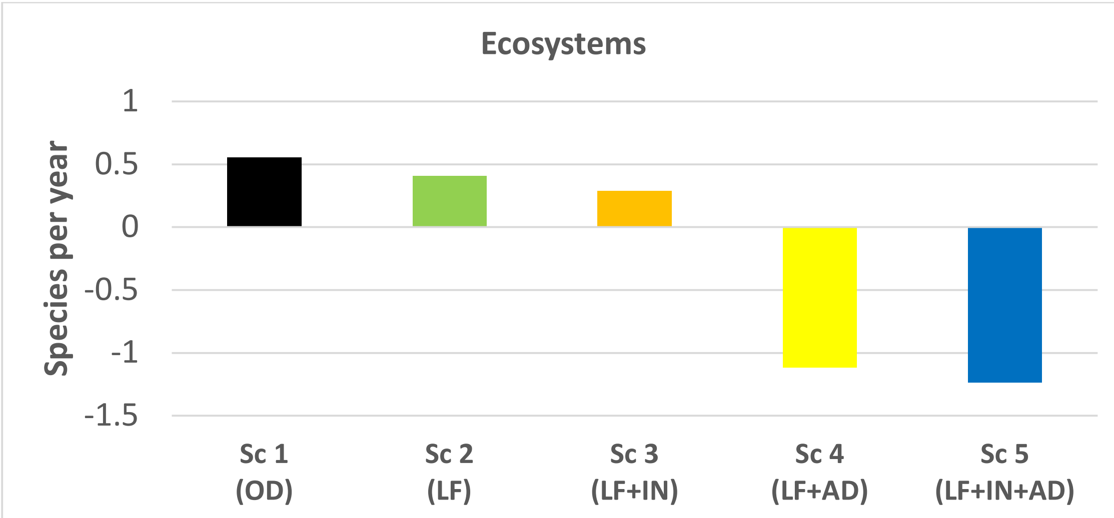

Figure 28 Results of Ecosystems

Discussion: Table 6 and Figure 28 reveal that Sc1 causes the most damage to the species. This is because its effects on terrestrial acidification are so great that they outweigh those of Sc2 and Sc3. Sc2 and Sc3 still have negative impacts on ecosystems, as stated in the intermediate impact categories, since landfills produce leachate, which is harmful to ecosystems in the long run. Since no leachate is created, Sc4 and Sc5 have a beneficial effect. Leachate may seep out of a landfill and pollute the groundwater and surrounding area if the liner fails. The Sc5 has a net beneficial effect on ecosystems, in contrast.

4.2.3. Resources

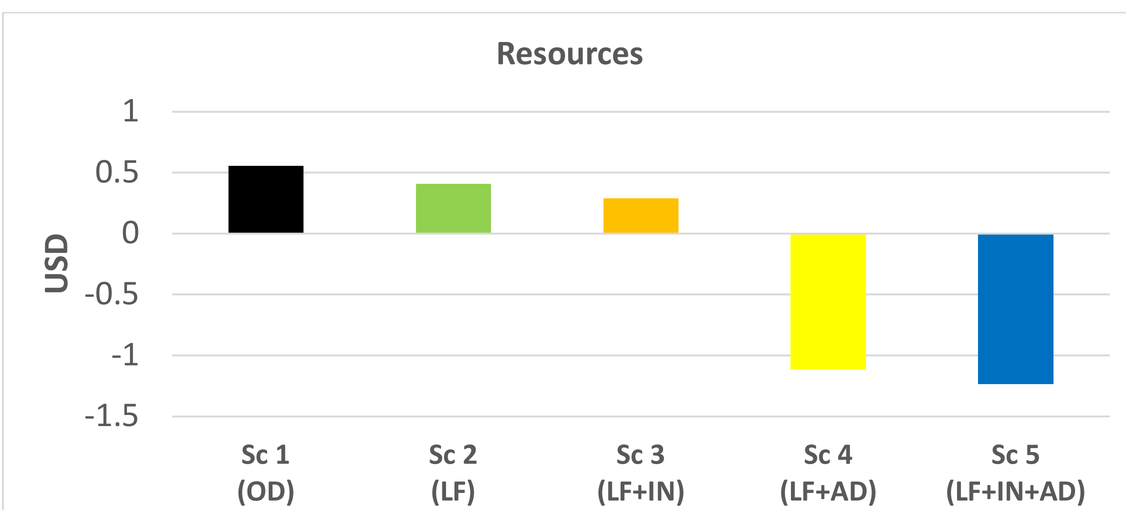

Figure 29 Results of Resources

Discussion: Table 6 and Figure 29 reveal that, among the median-impact groups, Sc5 results in the greatest resource savings. Sc1 has a negative effect since it contains no avoidable product.

4.3. Sensitivity Analysis

Figure 31 shows the environmental impact as measured by endpoint damage categories for a range of plastic waste recycling rates from 10% to 40% in 10% increments. It has been shown that negative environmental effects tend to lessen as the plastic recycling rate rises. The environmental effects of plastic waste may be mitigated to a greater extent with the help of MRF if it were implemented.

Table 7 Sensitivity Ratio for Plastic Waste

Description of Scenarios	**Equation for Finding SR Value**	**S.R Value**	**Remarks**
Sensitivity Analysis 40% MRF – 60% INCINERATION	$S.R = \left(\frac{\Delta\ result}{initial\ result}\right) \Big/ \left(\frac{\Delta\ parameter}{initial\ parameter}\right)$	0.9	Highly Significant

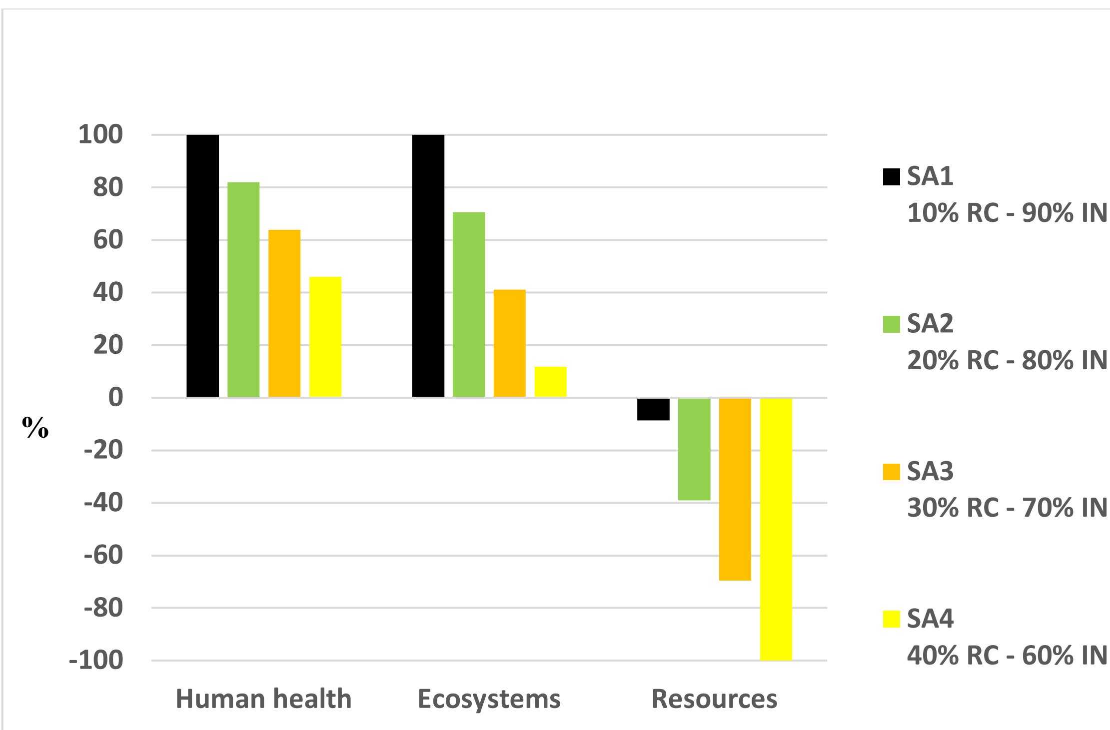

Figure 30 Results of Sensitivity Analysis for Plastic Waste

Chapter 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

This research looks at how the LCA method may be used to help with waste management decisions. The primary objective of this research is to assess the efficacy of potential technical solutions for MSWM in Peshawar, with the ultimate goal of enhancing the present MSWM system. Based on the findings of this study, it is clear that Peshawar's current MSWM system needs more attention and that new waste treatment or disposal methods are necessary to preserve human health and the environment. Results from LCA modelling (using SimaPro software) were used to draw the following findings about the evaluated MSWM solutions.

1. **Sc1** (open dumping of MSW in Peshawar) is the most environmentally damaging waste management strategy.
2. **Sc2**, which involves MSW landfilling, is the least favoured option, even if a high percentage of landfill gas recovery is achieved. Since more resources are utilised, including more fuel to compress the garbage and more land, MSW landfilling should be avoided if possible. In addition, if the landfill's liner breaks, leachate might leak into the groundwater.
3. **Sc3**, incineration of combustibles and plastics and landfilling of biodegradable and others, showed better results as electricity production is attained and recovery of biogas which is generated by disposing of the biodegradable waste in the landfill. Thus, resulting in negative net emissions, however, hardly any advantage when compared with Sc-4.
4. **Sc4**, anaerobic digestion of biodegradable and landfilling of combustibles, plastics and others, is better than Sc-1, Sc-2 and Sc-3, with respect of the environment and energy turnover when compared.
5. **Sc5**, anaerobic digestion of biodegradables, incinerating combustibles and plastics, and landfilling the others, is the best in terms of environment and energy turnover as avoided products like biogas and electricity. This scenario stands out to be most favourable system of MSW.

The LCA of MSW management systems include many uncertainties pertaining to the delineation of system boundaries, input data, and underlying assumptions. This research encompasses many crucial assumptions that has the potential to have a substantial influence on the ultimate outcomes of LCA. This study is based on the fundamental premise that the categories of "combustibles" and "plastics" do not include any recyclable components.

The results of the SA performed in this research show that plastics trash should get more attention since it contains recyclable materials. If you want to make it easier to collect recyclables, sorting your trash is a good idea. In light of the fact that many plastics have reusable components, recycling centres are preferred than incinerators.

Finally, it is possible to draw the conclusion that LCA may give helpful data for assessing various waste management strategies in less developed nations. Therefore, we utilised the Rest of the World (ROW) default values from the Ecoinvent database to reflect the existing conditions in Peshawar. However, LCA tools should be seen as a decision support tool that may give useful information but not take the place of a human decision maker.

5.2. Recommendations

The focus of this study is on the chosen MSW management system and technology. The studied MSW management methods are likely options for Peshawar, but other technologies should be investigated as well. Consequently, there has to be more research done to compare and contrast the various approaches of MSW management.

Adequate laws and regulations for MSW management in Peshawar need to be developed immediately. It is intriguing to see how the interdependencies between electricity generation and waste management are impacted by policy tools and technical developments.

This study focuses only on the environmental effects of Peshawar's current waste management system. In today's complex world, there are many considerations to examine while selecting the best waste management system.

Planning a waste management system with the community and economy in mind is essential for its long-term viability. To more accurately characterise the dynamics of the future socioeconomic technology waste system, social and economic LCA must be performed.

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