LIFE CYCLE ASSESSMENT OF MUNICIPAL SOLID WASTE MANAGEMENT ALTERNATIVES FOR ISLAMABAD, PAKISTAN

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A thesis submitted in partial fulfillment of the requirement for the Degree of Master of Science in Environmental Science

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Dedication

This research is dedicated to my loving, caring, and industrious parents and my best siblings whose sacrifices and efforts have made my dream of having this degree a reality. Words cannot adequately express my deep gratitude to them.

"O My Sustainer, Bestow on my parents your mercy even as they cherished me in my childhood".

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List of Abbreviations

AD	Anaerobic Digestion
BAU	Business As Usual
CDA	Capital Development Authority
EPA	Environmental Protection Agency
GHG	Green House Gas
ISO	International Standardization Organization
IMSWM	Integrated Municipal Solid Waste Management
LCA	Life Cycle Assessment
LCIA	Life Cycle Inventory Analysis
LCI	Life Cycle Inventory
LDC	Least Developing Countries
MCI	Municipal Corporation Islamabad
MRF	Material Recovery Facility
MSWM	Municipal Solid Waste Management
MSW	Municipal Solid Waste

ABSTRACT

The growing population and rapid urbanization in developing countries like Pakistan are consequently giving rise to an increased level of municipal solid waste to be handled. Municipal solid waste management is important in order to reduce the environmental impacts of mismanagement. Selection of optimal municipal solid waste management technologies while taking environmental sustainability into account is a challenge for decision-makers and specialists. Several waste management and treatment options are available, however, due to the complexity of municipal solid waste management, it is necessary to employ tools like life cycle assessment (LCA) to evaluate how various treatment approaches would have an influence on the environment. The objective of the study is to provide insights into the environmental implications of the existing waste management system in Islamabad, Pakistan and demonstrate the potential benefits of transitioning to more sustainable practices such as recycling, composting, anaerobic digestion, and incineration along with sanitary landfilling of the rest of the waste. For achievement of the objectives, life cycle assessment of municipal solid waste management alternatives for Islamabad was conducted using SimaPro 9.4.1 version and Ecoinvent 3.0 database. Five scenarios namely, S1 (unsanitary landfill-BAU), S2 (sanitary landfill+recycling), S3 (anaerobic digestion+recycling+sanitary landfill), S4 (composting+recycling+sanitary landfill) and S5 (incineration + recycling) for assessing the potential environmental impacts against each other and to assess potentially viable options were modelled. The functional unit of the study is 700 tons. Literature review, and Ecoinvent datasets from the SimaPro libraries were used for collection of data.CML-1A baseline methodology was used to evaluate the modelled scenarios for 8 midpoint indicators namely, abiotic depletion (fossil fuels), global warming potential, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, acidification, and eutrophication. According to the results, S1 (unsanitary landfill) for municipal solid waste which is the business-as-usual scenario is the worst management approach with highest environmental impacts followed by the S2 (sanitary landfill). Biological treatment methods for organic fraction of waste such as anaerobic digestion and composting along with recycling and sanitary landfill for other fractions of waste performed better and demonstrated environmental savings. S3 (anaerobic digestion) performed best with upto 106% improvement in environmental savings for global warming potential followed by S5 (incineration) and S4 (composting). The sensitivity analysis showed that increasing the recycling rate from 50% to 85% leads to increased net environmental savings for all scenarios with 104% increased net environmental savings for freshwater ecotoxicity in case of S5. The study showed that current waste management option has the most environmental impacts while an integrated waste management system with energy, resource and material recovery will generate net environmental savings and have least environmental impacts.

1. INTRODUCTION

With the increasing size of the human population around the globe, resource management issues have reverberated widely. High economic activity and urbanization have led to a delirious rise in municipal solid waste generation (Kundariya et al. 2021). Municipal solid waste can be described as the by-product of the objects used on a daily basis that is discarded. Municipal solid waste comes from various sources such as households, commercial buildings, and hospitals. Municipal solid waste is a mixture of furniture, tires, plastic, newspapers, packaging materials, containers, construction, and demolition as well as food and yard waste(US EPA, n.d.).

Although the composition of waste may vary worldwide, it generally has both biodegradable as well as degradable components. The data collected on the generation of municipal solid waste shows that in 2020, 2.24 billion tons of solid waste was being produced daily. It is estimated that the generation of municipal solid waste is increasing at a vigorous rate predicted to reach a level of more than 3.40 billion tons by 2050. The probable cause of the continuous increase the generation is an increase in population size as it is expected to reach 9.8 billion by 2050(The world bank 2020).

By 2050, it is anticipated that the total amount of waste produced in low-income nations will have increased by more than three times. The Middle East and North Africa area produces the least amount of garbage globally, at 6%, while East Asia and the Pacific account for 23% of global waste production. The developing areas, however, such as, South Asia, Africa as well as the North Africa and Middle East, where by 2050, it is anticipated that the total amount of waste generated will more than double, respectively (Figure 1). Over half of the waste in these areas seems to be presently disposed of openly, and the trajectory of waste development will have significant negative effects on the environment, human health, and economic growth, necessitating prompt response.

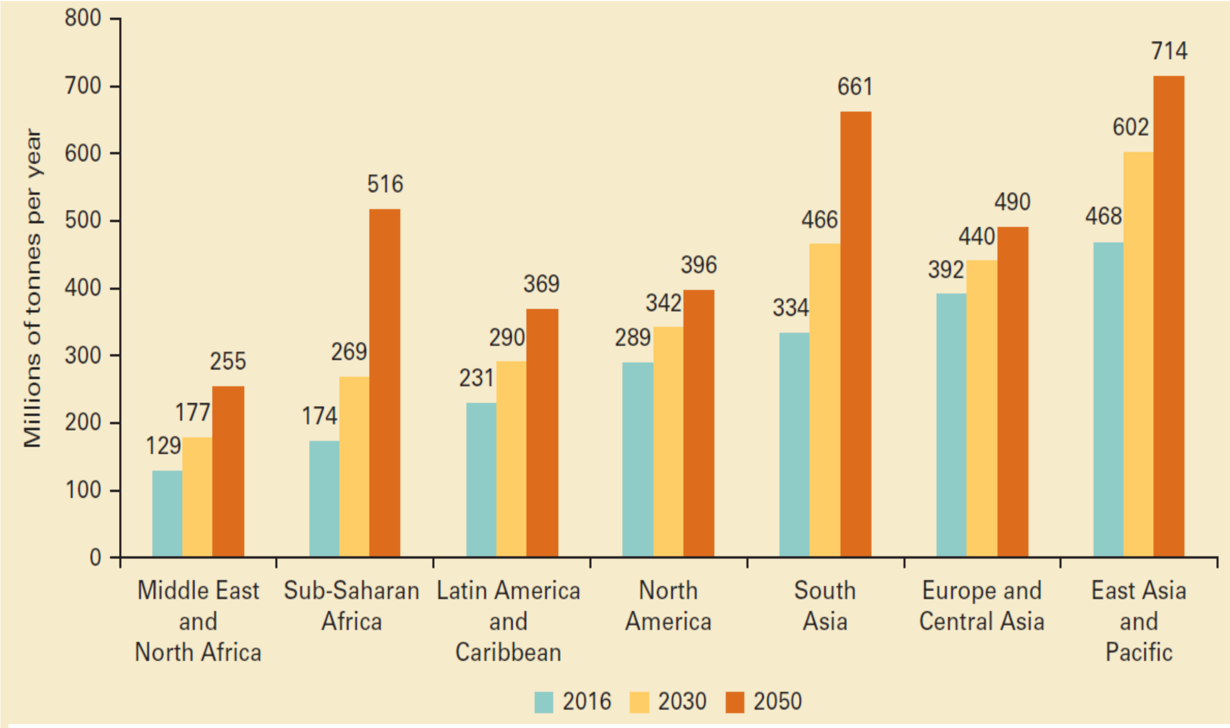


Figure 1: Projected generation of municipal solid waste worldwide from 2016 to 2050

Source: The World Bank, 2018

Thus, the increase in population and urbanization are leading to decreased carrying capacity of our planet. High generation of municipal solid waste has a lot of harmful impacts on the ecosystem as well as living beings due to its improper disposal and mismanagement. Municipal solid waste management refers to handling of waste in ways that render it less unpleasant and harmful. There are various methods of handling municipal solid waste that are applied by countries depending on their economic situation.

The management of municipal solid waste is a key issue of today's world for developing and developed countries(Kundariya et al. 2021). Efficient management of municipal solid waste is one of the important concerns that need to be addressed leading towards a better future. Common practices used for management around the globe include open dumping, landfilling, biological treatment methods as well as thermal treatment methods. Improper management of waste drives societies towards colossal economic and wellbeing issues(Istrate et al. 2020).

1.1 Solid Waste Management

Solid waste management is a very essential to achieve sustainability goals set for economy, environment and social justice. There are several factors that influence the process of waste management and contribute to the problem. The issues include but are not limited to lack of communication between the managing department and the community, political stability and governance and local's behavior towards waste handling. Due to improper waste management, most of the waste is not segregated or properly transported thus causing more problems on the way.

While solid waste management is associated to governance issues it also is somewhat affected by the country's demographics. A country's capacity to proper waste collection, disposal and recycling is pretty much dependent on its financial resources(Nanda and Berruti 2021). Therefore, there is a need to design separate waste strategies for different countries based on their real time status quo. Reliant on the country's waste generation and economic situation, a waste management strategy that is sustainable in every way should be designed thus, offering a more practical solution for municipal solid waste management.

Generation of municipal solid waste is an inevitable action that cannot be stopped but needs a post-occurrence disposal strategy. Management of the solid waste is necessary because of various concerns related to it such as health and environmental concerns. Major imperative drivers that lead to a waste management plan are environmental and public health, resource recovery as well as climate change (Vergara and Tchobanoglous 2012). The most important factor that pushes governments to pursue waste management is public health and protection of public health is the prime duty of the administrations. Improper disposal of waste can cause spread of diseases such as cholera and malaria(Krystosik et al. 2020).

Environmental health is also a concern of globally operational organizations that collect and analyze the data on degradation of environment. Visible environmental degradation help speed up the policy making and implementation process(Lamb et al. 2018). Resource recovery has always been a prioritized waste management route among others, it helps reduce waste sent for final disposal as well as usage to its full potential. Threats associated with rising greenhouse gas emissions are pushing industrializing nations to move towards an eco-friendlier waste management. Waste management strategies have a potential to become a sink of greenhouse gases (Puppim de Oliveira 2019).

1.2 Problem Statement of the Present Study

With the ever-increasing urbanization in metropolitan areas and the consequent high municipal waste generation, introduction of a sophisticated and sustainable method of waste collection has become a need of time. Although solid waste management might not be an issue to high priority for government and citizens of Pakistan owing to economic crisis and pertaining issues, it is an interlinked cause of many health-related issues. Solid waste constitutes of many different components present in variable amounts depending on the financial situation of the residents of the area. Hence to evaluate a better waste management option out of the ones available, it is very important to first know the waste composition of the concerned area.

Since Pakistan is a developing country, the organic content of waste generated on daily basis is usually high. On average, the moisture content of waste in Pakistan ranges from 55-60% In developing countries like Pakistan, a well-established waste management strategy is the need of the hour on one hand and financially not viable on the other. A potentially viable and sustainable waste management option needs to be evaluated soon in order to address the concerns arising from conventional methods.

1.3 Objectives of the Study

Thus, on the basis of the problem statement following objectives were set for the study:

1. To evaluate the environmental performance of the existing waste management system in Islamabad using LCA tool.
2. To show environmental improvements as a result of major changes in waste management approaches.

2. LITERATURE REVIEW

This chapter offers a thorough overview of the body of knowledge and research. To provide a conceptual framework and spot research gaps, it looks at pertinent scholarly books, research papers, and other sources. This chapter seeks to offer a theoretical foundation and context for the study by critically analyzing and synthesizing the existing material.

2.1 Introduction to Municipal Solid Waste

Municipal solid waste refers to all waste produced in a community, with the exception of waste produced by industrial operations and solid waste from the agricultural sector. Growing solid waste in emerging nations, particularly in municipal areas, is a serious issue that requires careful management. The history of waste provides insight into the societies that produce it, as well as data on their environment and resource usage. Municipal waste is any substance that has been used but is no longer wanted or useful. Rubber, plastic, metal, papers, cardboard, glass, biodegradable waste (kitchen waste, leaves, wood, and grass), animal manure, diapers, and other materials can all be found in solid waste.

Solid waste generation is influenced by a variety of variables; it differs region wise, country to country, society to society, and social and economic issues also play a role. Due to a lack of data and a challenge in choosing the right method, it can be exceedingly difficult to estimate and forecast the generation of solid waste(Edo et al. 2016). According to a USEPA report released in 2011, there was 250 million tons of municipal solid waste (MSW) created in USA in 2010. the figure totaled to 292.4 million tons in 2018. 25 million tons of the Waste generated was composted, and about 69 million tons was recycled. An estimated 4700 million tons of waste was recovered and composted in total, which equates to a rate of 32.1 percent for both procedures. Of this waste, 54% was dumped in landfills without being treated, which will have an adverse effect on the ecosystem(Anon n.d.-b).

Along with established nations, many developing nations like Malaysia also face challenges in managing the generation of solid waste. In 13 states of Malaysia waste generated on average is

17000 tons of domestic waste every day, or 6.2 million tons annually. The generation rates for major cities in per capita range from 0.5 to 0.8 kg per day, and it is rising daily as the population rises. About 80–90% of MSW is landfilled, and a respectable amount goes toward open dumping (Altwair, Megat Johari, and Saiyid Hashim 2012). Similarly in Least Developing Countries the solid waste generation rates of 0.56 kg/capita/day on average have been observed. Figure 2 represents average composition of solid waste in least developing countries of Asia.

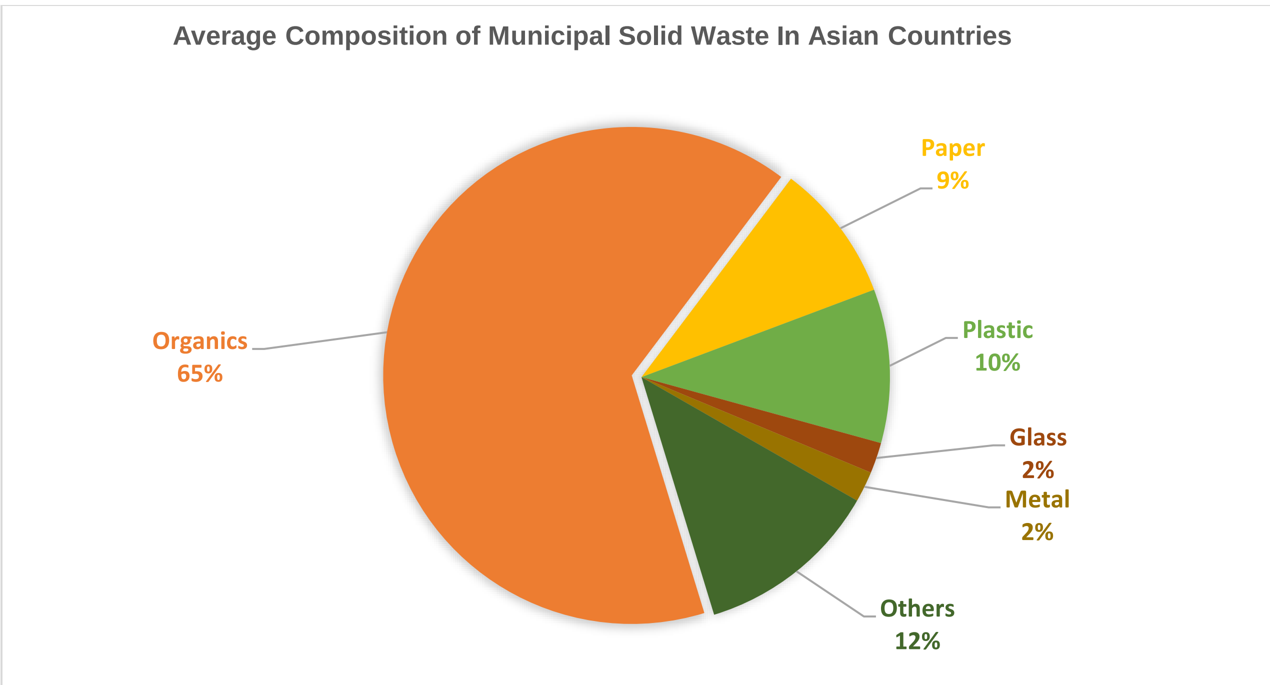


Figure 2: Average Composition of MSW in Asian Least Developed Countries

Source: (Bundhoo, 2018)

More than one trillion metric tons of solid waste were produced annually in 2000, and five billion tons are anticipated by 2030. Global ramifications will be severe if this crisis is not resolved quickly. Solid waste management is highly valued in many nations, and numerous innovative technologies have been created to enhance the waste management process(Nanda and Berruti 2021).

When developed and developing countries as United States of America are facing trouble in dealing with waste, this issue is becoming more severe for under-developed countries like Pakistan. Pakistan is struggling with urbanization, and the acceleration of industrial development is a significant factor in the rise in MSW output. According to estimates, 6 billion people worldwide will relocate to urban areas, tripling the world's population from 1960 to 2050, when it would be 9 billion. It demonstrates the worrying issue of the massive increase in municipal solid waste generation and the requirement for its efficient management(Korai, Mahar, and Uqaili 2017).

2.2 Municipal Solid Waste Management

The globe produces over 2.01 billion tons of municipal solid waste annually, and at minimum, 33% of that is not well managed. Unmanaged municipal solid waste is starting to cause a lot of problems(Dutta and Jinsart 2020). The steps that must be taken to collect, store, and transport waste must be taken seriously because they are essential to the treatment and management of solid waste(Joshi and Ahmed 2016). Waste segregation is becoming a more crucial issue as various waste elements require various modes of processing(Srinilta and Kanharattanachai 2019).

There are various issues with the Municipal Solid Waste Management plan in Pakistan, and they vary between cities. For instance, there is little or no primary collection at the doorstep, minimal recycling and sorting, minimal routine street cleaning, waste transportation in uncovered tractors/trucks, little waste treatment, and improper MSW disposal to dumpsites. The amount of facilities needed to process and dispose of the rising amounts of MSW in Pakistan is deficient. Due to this, waste has been dumped on land resources without following any regulations. This has resulted in huge mountains of rubbish that are a concern to public health since they are a source of air pollution and groundwater contamination (Hina et al. 2020).

At present, the world's annual production of solid waste is around 1.6 billion tons, and a significant amount of the budget is used for SWM. In the 1990s, in waste management alone, Asian countries spent about 2.525 billion annually, and this number is expected to increase to 5.050 billion by 2025(Aleluia and Ferrão 2016). The developing nations have not been able to adequately dispose of solid waste due to a lack of financial and technological resources. Despite the paucity of resources and expertise in the public sector, this creates a critical issue on how to deliver high-quality services.

Urban Solid waste management depends on accurate, quantitative calculations. Household waste is a significant component of municipal solid waste in metropolitan settings, and as such, it has a direct impact on the design of municipal solid waste management systems(Expósito and Velasco

2018). Wastes from the home, the workplace, and other sources also harm the environment. Consequently, municipal solid waste management (MSWM) is crucial for the growth of emerging nations in a sustainable manner (Azam et al. 2020).

2.3 Municipal Solid Waste Generation in Pakistan

Since 1998, Pakistan's population has been growing yearly by 2.4%, reaching an all-time high 207.7 million as of 2017, making it the sixth-most populated nation of world. Pakistan is rated 135th for worldwide methane emissions on a per-capita basis by the Pakistan Environment Protection Agency (Pak-EPA), generating less than 0.8% of the over-all worldwide greenhouse gas budget.

Additionally, unchecked municipal solid waste might promote the reproduction of dengue mosquitoes(Khalid and Ghaffar 2015). Due to the absence of any recycling regulations in Pakistan, just 27% (on a weight basis) of the total waste gets recycled(Maciej Serda et al. 2013). At various phases of municipal solid waste, waste pickers (needy individuals) manually gather and sell a lot of recyclables, such as paper, plastic, and metals, to unregistered junk shop owners (e.g., from generation to final disposal)(Azam et al. 2020).

The amount of solid waste produced in Pakistan annually, 49.6 million tons, has been rising by more than 2.4 percent a year. it is estimated that in Pakistan 0.5 to 1 kilogramme of household waste per day is produced, which is more than other developing nations have. Even though Pakistan has a low per capita head loss rate, waste management is still a significant issue.

For instance, only 50 of the 7,000 tonnes of solid waste that are produced daily in Karachi, Pakistan's largest metropolis, are collected by the municipality(Jabeen et al. 2022). The capacity of local governments and relevant agencies to collect waste is also a matter of concern because, on average, only 60 to 70 percent of solid waste in cities gets collected in Pakistan(Anon n.d.-c).

Data for municipal solid waste generation from different cities of Pakistan along with their population size is given in table 1. Karachi, which has a population of 20 million, creates 16500 tonnes of waste per day, whereas Quetta, which has a population of 0.6 million, generates around 700 tonnes of waste every day.

Table:1: Population wise solid waste generation rate of different cities of Pakistan

City	Population (Millions)	Solid waste generation (ktons/day)
Karachi	20.5	16.5
Lahore	10.0	7.69
Quetta	6.0	7.1
Rawalpindi	5.90	4.5
Peshawar	2.9	2.0
Hyderabad	5.50	3.9
Faisalabad	7.50	5.01
Gujranwala	4.8	3.4
Sargodha	4.5	3.0
Multan	5.20	3.6

Source: Project Procurement International

2.4 Municipal Solid Waste Composition

Composition of municipal solid waste depends on various variables such as purchasing parity, geographical location, income level as well as the population of the city under study. For instance, waste composition in rural areas is majorly composed of organic content such as kitchen waste and green waste while municipal waste of urban areas is majorly composed of packaging waste such as cardboard waste and paper waste. Presence of more organic content in the municipal waste is an indication of a lower to middle income(Zia et al. 2017). The physical aspects of municipal solid waste are also very important components that help determine their possible management options.

2.4.1 Municipal Solid Waste Composition in Pakistan

Pakistan is a developing country mostly comprising of middle-income groups and thus the moisture content of our waste is notably high. The municipal solid waste composition in Pakistan in general comprises of food waste, animal waste, green waste, textile items, rubber, metal, glass and paper. Table 2 presents municipal solid waste composition of various cities of Pakistan.

Table 2: Municipal solid waste composition of various cities of Pakistan

Waste Fraction	Abbottabad	Sahiwal	Lahore	Rawalpindi	Sialkot	Mardan	Peshawar	Sahiwal
Kitchen green waste	66.74	34.21	56.32	54.7	38.14	62.96	53.74	56.9
Paper	11.86	8.9	3.2	2.4	12.95	3.91	7.32	5.219
Textile	1.78	2.21	9.21	6.05	3.54	3.71	2.35	3.71
Yard waste	1.47	12.33	6.05	3.66	3.93	1.05	10.29	1.7
Plastic	9.46	9.67	10.64	10.51	10.22	7.36	9.34	9.54
Leather and rubber	1.07	0.54	1	1.2	3.2	0.61	0.63	0.88
Metal	0.08	0.58	0.06	0.03	3.2	0.2	0.72	0.375
Glass	0.75	1.96	0.69	0.64	7.13	0.87	2.32	0.75
Ceramic,stone, etc.	1.15	1.59	6.4	11.13	2	3.09	12.32	2.51
Miscellaneous	5.64	28.07	6.43	9.77	13.39	16.24	0.97	18.42
Misc	5.39	22.25	3.07	8.28	6	15.79	0.97	14.33

Source: Asian Development Bank, 2022

2.5 Effects of Mismanaged Municipal Solid Waste

People would throw rubbish openly on streets, plots, open dumps, and waterways in the lack of facilities for effective collection, which will degrade the land environment, surface and ground water, cause air pollution, and have a significant negative impact on human health. In fact, Pakistan recorded almost 40,000 instances of dengue virus infections in 2010 and in 2022, almost 26000 dengue cases were reported till September(Anon n.d.-a). History has a series of Plague episodes that are caused mainly because of poor environmental and unsanitary conditions. One such example from past is the past is Surratt an Indian city’s plague in 1994 which was a result of unhygienic conditions(Jayaraman 1995).

2.6 Advantages of Managed Municipal Solid Waste

2.6.1 Municipal Solid Waste as Energy Source

The country's economy relies on the availability of energy to support domestic, industrial, and commercial operations. The generation of energy has continued to be based upon non-renewable resources. The energy mixture of Pakistan is predominantly dependent on the extraction of energy from non-renewable sources, according an economic assessment conducted by the Pakistan government in 2015. 70% of Pakistan's energy needs were met in 1980 by the cheapest and most ecologically benign hydropower source. However, all of the elected administrations favored short-termed projects for energy generation owing to political unpredictability and budgetary restrictions, which brought the hydropower share down to 30%. Table 3 indicates average energy mix of Pakistan.

Table 3: Energy mix of Pakistan in electricity generation

Type of energy generator	**Share in electricity generation**
Thermal	64%
Hydro	27%
Nuclear	7%
Renewable	2%

Source: (Yaqoob et al. 2021)

2.6.2 Municipal Solid Waste for Promoting Sustainability

Since solid waste has a lot of potential to be reused, recycled and converted into by-products, it is a key component for promotion of sustainability. Increasing the amount of solid waste being collected and managed properly will consequently enhance the sustainable use of resources and their emissions. Even though sustainability can be incorporated into the concept of solid waste management. Many other factors also influence this concept such as proper waste collection systems, efficiency of the waste collection systems and also the efficiency of the waste managing department to collect funds and taxes to be used for upgrading the waste management systems.

2.6.3 Municipal Solid Waste as a Tool for Circular Economy

Instead of using linear economic models of use and discard, the circular economy focuses on sluggish material movements, segregation, material economy, and production efficiency, and without compromising economic growth, reduce the burden on extraction of resources(Ellen Macarthur Foundation n.d.). A circular economy targets constant product, component, and material use and value maximization and is revitalizing and recuperating by design. Circular Economy in case of waste management is a very important and refreshing concept as it deals with all the components of the solid waste according to their properties. for instance, metals, plastics and other material would be prioritized to be reused before recycled, organic waste could be composted to transfer the nutrients back to the natural environment and so on.

Municipal solid waste management is a topic of interest for the economists, the conservationists, the environmentalists as well as the socialists. there are multiple techniques of municipal solid waste management and hence selecting one that is feasible and would work best in certain conditions is very important. A solid waste management design that is successful in a country might fail in another due to differences in the composition of the waste and hence the efficiency of the waste management option and the economic condition of the country as selecting an option that is feasible to be used in long term shall always be prioritized.

2.7 Assessment Methods for Best Municipal Waste Management Practice

Municipal solid waste and the environmental effects linked to its management have drawn more consideration globally since 1960s. The choice of the optimum solution gets more challenging as waste management grows more complex. As a result, system analysis and computational analysis were created. Traditional models appear to prioritize economic optimization above potential environmental effects. Ever since, the environmental effect as well as energy and material recovery have received more consideration in Integrated Waste Management planning. Eventually, it became clear that environmental and socioeconomic variables are equally important(Abou Najm et al. 2016).

Several evaluation techniques have now been created to assist in waste management decision-making. The evaluation tools might frequently be split into two groups' procedure tools and analysis tools. Measures and decision-making situations in the world and the environmental settings are often covered by procedural instruments (such as the Environmental Management System (EMS)). These later tools—like LCA, for instance—typically offer data that may be utilized for system optimization, alternative comparison, collaboration, etc. But procedural tools are commonly used in conjunction with analytical tools(Finnveden and Moberg 2005). Factors that generally effect the selection of the tool are the scope of the study, the type of decision to be taken, the scope of the decision as well as the validity of the selected tool.

Life cycle thinking, particularly LCA, has achieved widespread acceptability in comparison to many other decision-support methods because it consistently produces conclusions that are relevant to policy(Finnveden and Moberg 2005)**.** It may be utilized both as a descriptive tool and as an instrument that focuses on change, depending on the data and approach employed. LCA was originally established to evaluate the entire life cycle of products, together with resource extraction, manufacture, distribution, use, and disposal "from cradle to grave," and is described in ISO 14040 as a tool aimed at assessing the ecological consequences and intake as well as consumption of resources.

In addition to product mechanisms, the term "product" can refer to service systems as well, such as waste management. Life cycle assessments is now one of the most widely used techniques for assessing environmental elements and possible effects of human actions, such as waste management procedures, from the cradle to the grave (final disposal, replacement of raw materials). LCA is a useful technique to determine the financial costs and environmental impacts of Integrated Municipal Waste Systems.

2.7.1 Life Cycle Assessment Tool

The LCA was first created for analyzing the entire life cycle of products, together with resource mining, manufacture, distribution, use, and disposal "from cradle to grave," and is described in ISO 14040 as a tool to evaluate the ecological consequences and consumption of resources (ISO 2006). "To describe and enumerate the service given by the product, to detect and measure the environment trades generated in a manner which the service is supplied, and to assign such trades and its possible repercussions to the service" is how environmental evaluation of a product is defined (Pesonen et al. 2000).

LCA is now one of the extensively used techniques for assessing environmental elements and possible impacts of hominid actions, such as waste management procedures, from the cradle to the grave (end disposal, replacement of raw materials). LCA is a useful method for determining the financial costs and environmental impacts of Integrated Municipal Waste Management Systems.

2.7.2 Methodology of Life Cycle Assessment Tool

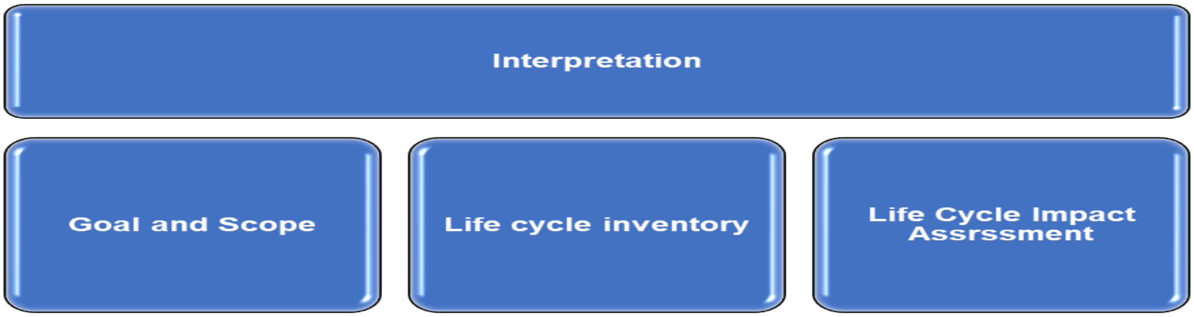
ISO 14040 standards are applied for carrying out life cycle assessment which consists of a series of standards i-e, ISO 14040,ISO 14041, ISO 14042, and ISO 14043. According to ISO standards, an LCA must follow a systematic approach and consist of four main stages as follows:

Goal and Scope: Attempts are made to establish the purpose and scope of the investigation as well as the approaches that will be employed to carry it out in subsequent phases. The goal and scope define the most significant choices, which are usually arbitrary. As an illustration, a thorough explanation of the product and its life cycle, the rationale behind conducting the LCA, as well as a summary of the system's limits is all included in the goal and scope. During this defining step, one chooses a system boundaries, product system components, and functional units strategies, and effect categories.

Life Cycle Inventory: LCI is the process of identifying the activities that are involved and gathering and allocating all pertinent data. We scrutinize all of the environmental inputs and outputs associated to a good or service whilst performing an inventory analysis. An example of inputs would be the amount of energy and raw materials compulsory for the process while the output would be resulting emissions to air, water or soil.

Life Cycle Impact Assessment: Allocating inventory figures to effect and resource groups is known as life cycle impact assessment (LCIA). In the LCIA step, we conclude results on the basis of our Goal and Scope as well as Life Cycle Inventory. Normalization and weighting can also be integrated depending on the requirements of the project. Weighting might be used to combine indicator findings from several effect categories and transform them into one final single result. Another possible component is normalization, which compares the effect magnitudes to benchmark values, such as the overall contribution of each nation to an impact category.

Interpretation: During this phase we make sure that we obtained well-substantiated results. A repeated process of analyzing the Life Cycle Inventory and the Life Cycle Inventory Analysis until the outcomes are in line with the objective and the scope, as well as reliable suggestions and inferences can be drawn on the base of sensitivity analysis.



2.7.3 Using Life Cycle Assessment for Assessing Waste Management Methods

Currently, LCA is utilized to assess various integrated solid waste management strategies and to assess available management possibilities for distinct waste components(Finnveden and Moberg 2005). To make the computation for repeated waste management process units easier, computer-based models and databases were created. There are different LCA software that have the adequate database to carry out LCA of integrated waste management or comparisons of different alternatives for improved management of municipal solid waste. Some of these software are OpenLCA, Easetech, GaBi and SimaPro.

Silva et al., (2021) compared four waste management scenarios for the capital city of Brazil, Brasilia. The study evaluated four municipal solid waste (MSW) management scenarios, three of which included incorporating RDF production into the currently employed methods, while the fourth scenario exclusively included landfilling. SimaPro 8.4.2 was used with Ecoinvent 3.0 database. According to the findings, the MSW management system in place emits 267.44 Gg CO_2-eq of greenhouse gases annually. According to the research, compared to the standard procedure, scenarios that included RDF production resulted in greater energy use and overall GHG emissions. These scenarios did, however, demonstrate positive environmental effects when taking into account the saved emissions brought on by the replacement of fossil fuels. RDF usage and production beat conventional methods, resulting in emission reductions ranging from 2% to around 23%. Additionally, employing RDF-oriented management could greatly lessen the effect on the capacity of the nearby landfill site. Recycling and composting in the given scenario led to a minor 0.12 Gg Sb-eq/year decrease in the depletion of abiotic resources. However, the reduction in the depletion of abiotic resources ranged from 3.63 to 13.73 Gg Sb-eq/year when the prevented extraction of related fossil fuel reduction was taken into consideration. The study's findings highlighted the benefits of RDF-based scenarios for the environment, taking into account the decrease in indirect GHG emissions and resource use.

A study utilizing the life cycle assessment approach was presented by Gadaleta et al., (2022). The approach used in this study to evaluate and compare the sustainability of various waste management plans is based on multi-criteria decision analysis (MCDA) and life cycle assessment. The southern Italian city of Bari is the subject of the case study. Three waste management strategies are considered: a door-to-door system with a good (>80%) source separation rate (S2), a bring point and door-to-door system coupled with a 35% source separation rate (S1), and a combination system with a 70% source separation rate (S3). The remaining fraction from source separation is handled differently in each scenario, either by mechanical-biological treatment (Scenarios S1 and S2) or recyclable recovery at a material recovery plant (Scenario S3). Employing MCDA and LCA techniques, sustainability was assessed while taking into account socio-technical, economic, and environmental factors. Results indicate that S2 performs well in terms of environmental and socio-technical parameters, making it the most sustainable option overall. In contrast to the other possibilities, it has a larger cost per capita. Notably, S3 differs somewhat from S2 in the environmental and socio-technical parameters by around 5.4% and 9.4%, respectively, indicating that the mixed collecting mode is very competitive and advantageous.

A study conducted using life cycle assessment approach in Rawalpindi, Pakistan in order to determine the environmental effects of the Rawalpindi Waste Management Company (RWMC) value chain in Pakistan over a three-year period (2015-2018). The energy potential of municipal solid waste through the year 2050 was also forecasted by the study. SimaPro v.8.3 software was used to analyze inputs and outputs data using 1.0 tons of municipal solid waste as the functional unit. The CML 2000 methodology and the cumulative exergy demand indicator (CExD) were applied. With 8962.83 kg 1,4-DB eq per ton of MSW, the LCA results showed that RWMC's operational activities were predominantly responsible for marine aquatic ecotoxicity. This is due to the long-distance transfer of petrogenic hydrocarbons from the fleet's petrol combustion. According to projections for the country's energy needs up to 2050, the MSW from Rawalpindi city may generate 3901 megawatts of electricity, which would be a considerable contribution.

Reducing reliance on fossil fuels and petrogenic fuels for transportation, streamlining waste collection and disposal routes, researching appropriate waste-to-energy conversion technologies, and implementing an all-encompassing approach to MSW management in Pakistan are some potential mitigation strategies for environmental effects in the MSW management value chain(Li et al. 2018).

Another study assessed and compared two management options for the treatment of organic component of municipal solid waste in Rasht City, Iran, namely composting and anaerobic digestion, from the standpoint of environmental sustainability. The environmental effects of composting and anaerobic digestion of the organic part of municipal solid waste were assessed using the life cycle assessment method. The study's functional unit was 100 tons of municipal solid waste, and the system boundaries covered all activities involved in transporting that waste from the city through each scenario's production process. The findings demonstrated that when treating organic wastes via anaerobic digestion as opposed to composting, damage to the environment was reduced by 66.67% for human health category, 47.84% to ecosystem quality and 89.64% to climate change. The study's results demonstrated that the treatment of organic wastes to create energy and value-added materials had positive effects on the environment(Behrooznia, Sharifi, and Hosseinzadeh-Bandbafha 2020).

Through life cycle assessment (LCA), a study evaluated the historical GWP of MSW management in Nottingham from April 2001 to March 2017. Based on the findings of the inventories conducted using the IPCC 2013, GWP 100a method, the life cycle impact assessment was classified by GWP at a 100-year time frame (GWP100). The LCA findings show that advances in waste collection, treatment, and material recycling, as well as waste avoidance, resulted in continual decreases in greenhouse gas (GHG) emissions from MSW management over the course of the research period. A net greenhouse gas reduction of 1076.0 kg CO_2-eq./t of MSW in 2001-02 to 211.3 kg CO_2-eq./t of MSW in 2016-17 as a consequence of these advances was observed. This is mostly because waste has been diverted from landfill to more environmentally friendly management choices including recycling, composting, and incineration. S1 has the greatest GWP100 potential among all historical scenarios because more than half of MSW was landfilled without any treatment. By separating food waste from incinerated waste, treating organic waste with anaerobic digestion, and pretreating incinerated waste, it is possible to reduce MSW emissions even more, to 142.3 kg CO_2-eq./t of MSW(Wang et al. 2020).

A study was conducted in Nagpur, India by Khandelwal et al., (2019) to assess the effects of the municipal solid waste management system under four scenarios namely composting and landfilling (S1), material recovery facility and composting (S2), material recovery facility and anaerobic digestion (S3), and material recovery facility, anaerobic digestion, and composting together (S4) analyzed using LCA tool. Using the CML-1A impact characterization approach and the Gabi 8.5.0.79 model, the scenarios were compared. In terms of eutrophication, human toxicity, global warming, and the potential for photochemical ozone formation, S2 was determined to have the least negative effects on the environment. According to the sensitivity analysis, the overall environmental impacts and changes in recycling rates are inversely related and thus increased recycling rates lead to positive environmental impacts(Khandelwal et al. 2019).

Another study conducted in India using SimaPro (version 8.1.1) software and CML-2 baseline methodology conducted life cycle assessment of municipal solid waste management strategies for tricity region of India. The approaches investigated included waste transportation and collection (A), recycling, composting (B), landfilling (C), and other pertinent methods. In order to evaluate the effects across several categories, quantitative data was gathered. Measurements were taken for greenhouse gas emissions, energy use, resource depletion, and water and air pollution. Background information was gathered from reputable sources and Ecoinvent database, while primary information was gathered through sampling and questionnaires. The results showed that the methods differed significantly from one another. For instance, compared to Strategy B, Strategy A reduced greenhouse gas emissions by 30%, while compared to the baseline scenario, Strategy C reduced energy usage by 50%. Comparing Strategy D to present practices, water pollution was significantly reduced by 60%(Rana, Ganguly, and Gupta 2019).

A life cycle assessment to compare the environmental effects of different on-farm organic waste treatment strategies, including anaerobic digestion (AD), composting, and AD followed by composting was conducted in China. The potential environmental impacts of various waste management strategies were assessed using OpenLCA (version 1.5.0) software based on their acidification potential, ecotoxicity potential, eutrophication potential, global warming potential, and resource depletion. The Ecoinvent 3.2 database served as the basis for the data used in this investigation. The study discovered that the best method for treating dairy manure was to combine the use of maize stover and tomato residue with solid-state AD technology. With reductions of more than 40% from the present condition, solid-state AD of tomato wastes, maize stover, and dairy manure was also very favorable in terms of AP, EP, and ETP. AP, EP, ETP, and GWP. The scenario analysis on transportation distance showed that having the AD plant and composting facility on the farm was favorable for all life cycle effect categories(Li et al. 2018).

In order to investigate the environmental effects of several municipal solid waste management scenarios in Dhanbad City, India, Yadav and Samadder, (2018) used life cycle assessment (LCA). Four different scenarios were taken into account: collection and transportation (S1), the baseline scenario (S2), composting and landfilling (S3), and recycling, composting, and landfilling of inert waste (S4). One metric tonne of municipal solid waste (MSW) served as the functional unit. While background data was gathered through SimaPro 8.1 libraries, primary data was gathered through sampling, questionnaires, and reading. For comparison, the CML 2 baseline 2000 approach was employed. Results indicated that S1 had the greatest effects on abiotic depletion and marine aquatic ecotoxicity. The most significant effects of S2 were on global warming, acidification, photochemical oxidation, human toxicity, and eutrophication. The least preferred method of waste disposal was found to be landfilling without energy recovery. S4 was suggested as the most ecologically friendly technology for MSWM in Dhanbad City(Yadav and Samadder 2018).

To investigate the environmental effects of various municipal solid waste (MSW) management scenarios for Mauritius, the research used life cycle assessment approach. Composting, incineration, and landfilling (S1), incineration with energy recovery (S2), incineration and landfilling (S3), and composting, recycling, incineration, and landfilling (S4) were the scenarios that were modelled for LCA. The functional unit was the MSW produced in year 2010. Background data was obtained from the Ecoinvent database in SimaPro 8 libraries, whereas foreground data came from surveys and books. Both the CML-IA baseline-midpoint and ReCiPe endpoint methodologies were used to conduct the evaluation. Results from the midpoint method showed that S1, with the exception of ozone layer depletion and human toxicity, had the greatest influence on the majority of damage categories. With the exception of potential for global warming and human toxicity, S2 had the least influence on the majority of damage categories. S3, which included composting, had negative effects because of the composting procedure.

Considering S2 (incineration with energy recovery) and S4 (composting, recycling, incineration, and landfilling) in the strategic planning of MSW management was advised by the study(Rajcoomar and Ramjeawon 2017).

Life cycle assessment for source-separated waste collection and integrated waste management was conducted for Hangzhou, China. Using the yearly municipal solid waste generation in the city i-e, 2.5 million tons as the functional unit, this study analyses four municipal solid waste (MSW) management systems. In scenario 1, a mixed collection system is used, with 50.77% of the MSW being landfilled and 49.23% being burned. Scenario 2 is a representation of the existing source-separated collecting system. Two more future MSW management strategies were modelled as well. An incineration facility was considered as part of scenario 3's short-term plan, and scenario 4's long-term strategy is the introduction of biological treatment methods for food waste. Danish EDIP 97 methodology was used for calculating life cycle impact assessment. The findings show that source separation has major environmental advantages. It inhibits 30%, 18%, 28%, and 29% of photochemical ozone production, acidification, nutrient enrichment, and global warming, respectively. The management of MSW over the long and short terms has a favourable impact on the environment. Additional sensitivity analysis emphasizes the value of the biological method for treating food waste, especially in view of ongoing source separation efficiency improvements. For a beneficial environmental outcome, effective control of MSW going to the landfill is also essential(Chi et al. 2015).

3. METHODOLOGY

This section contains information about the investigation's scope and the opted research process. The goal of this chapter is to provide a thorough and comprehensible overview of the study's methods and the procedures. The research's theoretical framework, data collection methods, and methods for analysis are included in the methodology. Thus, the chapter presents the groundwork for the subsequent analysis and interpretation of the data.

3.1 Life Cycle Assessment as Assessment Tool

A product's life cycle study can be performed using LCA tools. It enables the evaluation and comparison of a product's environmental effects using particular databases. SimaPro is such software tool that helps allow conduct entire life cycle analysis of products. The sustainability software's strong foundation in sound science and life cycle reasoning makes it ideal for product designers, decision-makers, and sustainability experts. With the help of its fact-based LCA methodology, improved decisions can be made, better options can be developed, and the environmental effects of products and services can be reduced.

The majority of life cycle evaluation software rely on datasets that are unique to the concept of circular economy. Both broad ranged and specialist databases exist and are chosen on the basis of domain of the product under consideration and life cycle system boundary. The database used in this study is Ecoinvent database. It is a Life Cycle Inventory (LCI) database that enables different kinds of environmental evaluations. Users can learn more about how their goods and services affect the ecosystem thanks to the Ecoinvent Index.

This is a collection that covers a wide variety of worldwide and regional industries. It presently includes over 18000 operations, also known as "datasets," that represent different processes. Ecoinvent datasets include data on the industrial, agricultural process they model and waste treatment methods, including measurements of the natural resources used, the emissions released into the air, water, and soil, the products needed from other processes (such as electricity), and of course, the products, co-products, and wastes produced.

3.2 Study Area Selected for the Present Study

Islamabad is the capital city of Pakistan situated in the northwestern side of Pakistan in Potohar plateau. Situated at latitudes of 33°49’N and longitudes of 72°24’ east, it covers a total area of 65 sq.km as a city and 906.5 sq. km is the total area of Islamabad Capital Territory that would be expanded and urbanized with time. The city houses a population of 1.1 million people in the metropolitan area and an estimated 2 million population inclusive of suburban areas. It is considered among some of the most beautiful capitals in the world due to its scenic view and greenery. Islamabad was declared the capital of Pakistan in 1963. The city was built based on a thoughtful grid-based master plan prepared by a Greek firm by the name of Doxiadis Associate.

Islamabad has a hot and humid subtropical climate, with hot and humid summers, a monsoon season, and cold winters. The typical yearly rainfall for the city is 1143 millimeters with an average humidity recorded at 55%. The city has served as a crossroad between northern areas of Pakistan and Rawalpindi division. Islamabad is among the most rapidly urbanizing cities due to abundance of employment and business opportunities. People from all across Pakistan come here to seek employment or establish their own business. All major embassies and consulates as well as the Foreign Office, are based in Islamabad from where all the diplomatic relations with other countries

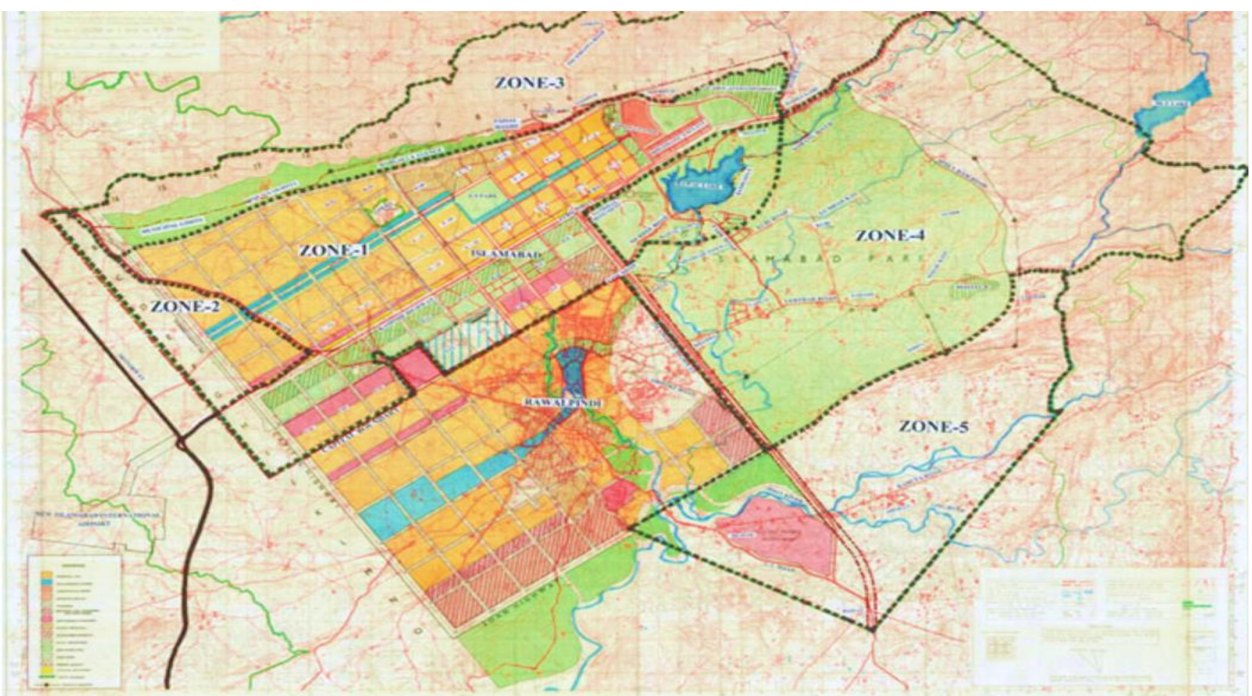


Figure 3: Study area map of Islamabad

are maintained. Figure 3 displays the overall map and zone division of Islamabad which is our study area.

At first the city only consisted of one zone which was further redistributed into five zones named from I to V. The area covered by Zone 1 is 222.4 sq.km. It is the most well-kept and attractive suburb of Islamabad, and key sectors including H-8 to H-13, I-8 to I-13, F- 6 to F-14, G-5 to G-14 as well as the undeveloped rustic zone of Golra village, are all located in Zone I. Zone 2, which is 39.6 sq.km, is connected to Zone 1. The pace of growth in this area was quite modest until recently. Zone 2 is the second-most valued investment zone in the city, next to the New Islamabad International Airport, the GT road, and motorway.

Zone 3 of the city covers an area of 203.9 sq.km. This area is home to tourist destinations like Dama-e-Koh and Peer Sohawa. Zone 3 has been able to keep its rural allure and peaceful atmosphere since CDA has placed restrictions on residential and commercial development plans there. This zone also includes a few of the older Margalla Hills villages, such as Saidpur, Shah Allah Ditta, and Talhar. Zone 4 is by far the largest zone in Islamabad, covering an area of 282.5 sq. km. Zone 4 is home to some of the most well-known housing developments, such as Bani Gala, and Bahria Enclave. There are more lakes here called Rawal Lake and Simli Dam Lake. This zone was designated for agro farms in the CDA master plan, and in order to preserve that designation, officials agreed that no new residential development would be approved there.

Following the establishment of CDA's zone 1, zone 5 covering an area of 157.94 sq.km was established. It swiftly developed into a densely populated area as a result of the old airport's close proximity. For Zone 5, the CDA has approved a number of private and cooperative housing projects. Notable ones in this area include Bahria Town, the PWD, and the Defense Housing Authority. various tourist spots are in the city including Pakistan Monument, Shakarparian, Margalla hills and hiking trails, Damn-e-Koh, Shah Allah Dita buddhist caves as well as Loke Virsa cultural center.

An executive order named the Pakistan Capital Regulation, which was issued on June 24, 1960, was followed on June 27 by the CDA Ordinance, which formed the Capital Development Authority (CDA) on June 14, 1960. CDA is the responsible agency as a regulatory authority for public safety, environmental standards and building codes. As a maintenance agency for public areas such as parks and public infrastructure and as planner for development of new projects.

Previously CDA used to collect waste from Islamabad but in 2022, Metropolitan Corporation Islamabad was given the charge.

The city generates 1000 tons of waste per day on average. This waste is generated by the municipalities of all 5 zones of Islamabad. The waste is collected by workers assigned by MCI. The average municipal solid waste collection rate of Islamabad is 70% while 30% is left in streets unattended.

3.2.1 Waste Generation Rates of Islamabad

Waste generation rate were also obtained from Capital Development Authority. The waste generation rate taken in this study is 1000 tons per day. The waste collection rate of CDA is estimated to be 70% hence, calculation have been done for 700 tons of municipal waste collected per day.

3.2.2 Dumpsite/ Waste Treatment Facilities in Islamabad

For this study the dumpsite for municipal waste at I-12 has been taken. It has been assumed that all the waste treatment options are present at the dumpsite. All the waste treatment options considered in this study are assumed to be at the same location as the dumpsite. The total land area covered by dumpsite used in this study is 0.186 km2a.

3.3 Goal and Scope of the Study

The goal of the study is to evaluate the impacts of various waste management scenarios for Islamabad using different environmental indicators. The tool was chosen as a support method to estimate the effects of different waste management techniques using the cradle to grave approach for Islamabad. The primary issues with this study's limitations were the lack of inventory data in Islamabad and consistent methodologies. However, the environmental information acquired in this study is adequate to conduct an evaluation of MSW because there hasn't been an environmental assessment of municipal solid waste in Islamabad.

3.3.1 Functional Unit of the Study

While conducting life cycle assessment, functional unit is one of the key element to determine the way forward. Functional unit could be characterized as an evaluation of the Product System's functional outputs, and it offers a benchmark against which inputs and outputs can be compared(R. et al. 2008). The functional unit will also serve as a benchmark for comparison with other systems or scenarios. Otherwise, it will be impossible to compare LCA studies in a fair and equal manner. The primary research findings for the impact assessment are provided in relation to a functional unit of 700 tons of municipal solid waste of Islamabad.

3.3.2 System Boundary of the Study

Unit processes that need to be encompassed in conducting a life cycle assessment are determined in a system boundary. Material and energy transfers across system boundaries are the foundation of LCA. In this study, SimaPro model boundaries were used as system boundaries that cover bin-to-disposal, i.e., from the point where products become waste and are put in the waste bin at the waste collection point to the point where the waste has either been transformed into a valuable material or has turn out to be part of the environment after final disposal, as shown in Figure 4.

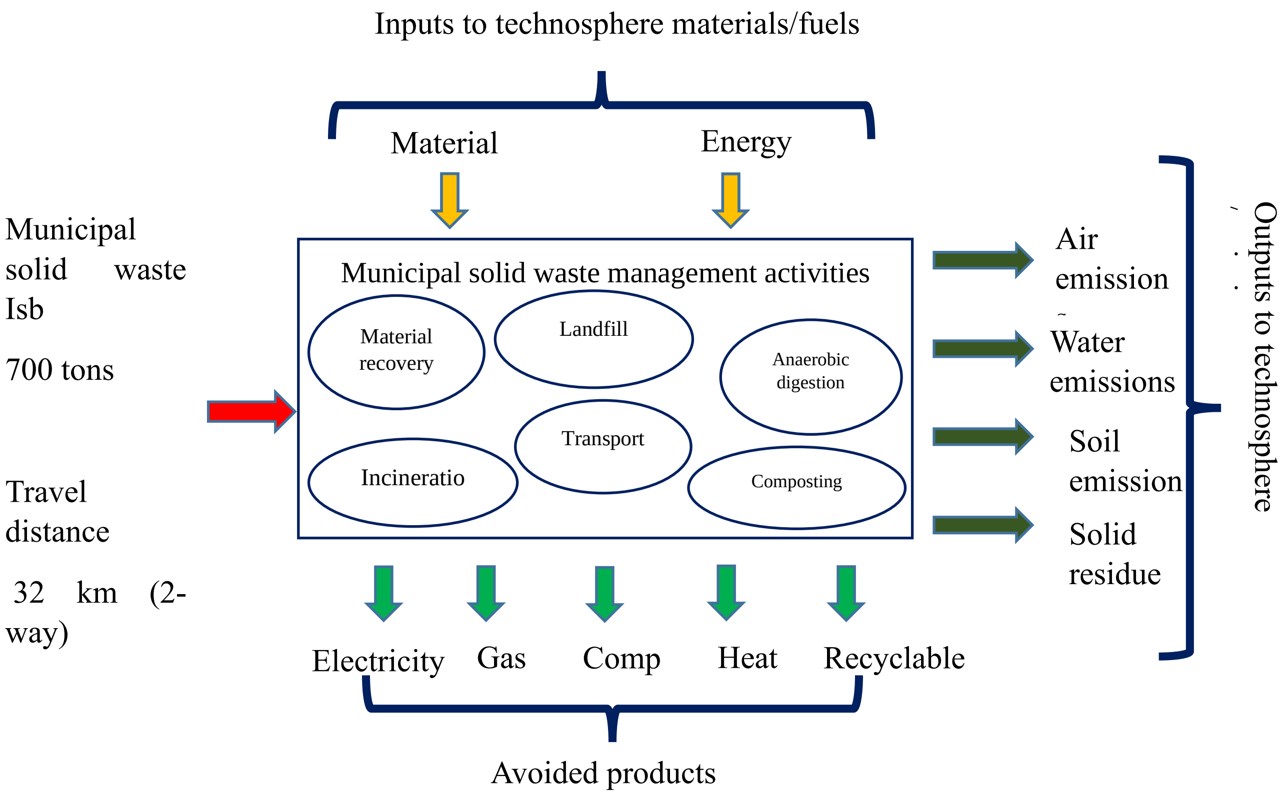


Figure 4: System Boundary of the study

The system being analyzed is known as the foreground system, while the background system is the environment in which the foreground system functions. The foreground system's processes could take the place of some background system processes. For instance, the manufacturing of goods or services using virgin resources is replaced by waste recycling.

In this study we have used system expansion approach. Externalities of a system or product are considered in the evaluation of system growth. Allocation also attributes the system’s environmental effects to its constituent parts. The ISO standards for life cycle assessment leave a large deal of room for flexibility and can be implemented in many ways because many impact allocation concerns are difficult to answer. The system expansion approach allows utilization of “avoided products” concept. Avoided products can be termed as the outputs of the products that substitute or replace themselves from the system’s inputs.

Composting, digestion, recycling, incineration, and landfilling are all included in the front system for different waste management scenarios in the SimaPro, which also includes waste collection from a single collection point and transportation. The activities that are not directly affected by the actions made in the foreground system, such as systems for producing power or raw materials, make up the background system. Analyzing the environmental impacts of goods (such as power or recycled materials) entails examining the environmental impacts of the extended system boundaries' background system, i.e. the generation of energy and virgin materials.

This boundary excludes the manufacture of capital products, equipment, and ancillary infrastructure like buildings and roads. The effects of domestic waste generators' actions on the ecosystem municipal solid waste, waste management, waste management, waste gathering & transportation process as well as of waste reclamation and recovery The relationship between municipal solid waste management materials, basic materials with additional vitality emissions to air, water & soil (e.g. cleaning refuse containers, resident driving to a garbage processing center, etc.) are also omitted from the modelling. The waste composition and quantity, output of both goods and byproducts, and accompanied emissions are all taken into consideration by the model to describe the emissions.

Waste collection from a collection point, use of land for waste disposal, material sorting at a materials recovery facility (MRF), recycling of material, waste disposal to landfills without any treatment, biological waste treatment methods such as anaerobic digestion and composting, thermal treatment methods such as incineration, waste disposal to landfill, material utilization, and energy utilization are the subsystems considered in this study. All environmental effects across the system boundaries and credits from energy retrieval were evaluated in this study and covered by the LCA model.

The life cycle assessment for determining a sustainable option in Islamabad city considered recycling of paper and cardboard, plastic, aluminum, and steel, which are primarily the greatest secondary materials, from sorting to manufacturing. The handling of other waste streams, such as demolition and construction waste, is not addressed because SimaPro was primarily intended for waste types from households and small commercial business units. Electrical and electronic equipment, which are bulky and inert parts of household waste, were not part of the study since they are processed and handled separately.

3.3.3 Scenario Modeling for Life Cycle Impact Assessment

To find a suitable waste treatment option for the municipal solid waste of Islamabad, five scenarios considering different waste management techniques were developed using SimaPro.

3.3.3.1 Scenario 1: Business as Usual; Open Dumping

Scenario 1 is the business-as-usual scenario of this study. In this scenario, it was considered that 100% of waste goes into landfill without any treatment. In Islamabad, a single waste trunk is used to collect all types of waste as there is no waste segregation observed. Except for a few private ventures, the waste collection mechanism in Islamabad is quite old and traditional with no emphasis on waste segregation or its usage as a resources. Waste collectors are appointed who collect waste from door to door with charges and from a street or community designated dustbin on daily basis.

Diesel powered lorries are used to transport this waste to the dumpsite located in I-12. This allows no waste treatment neither thermal nor organic. All type of waste including organic waste ends up at the dumpsite. The only alternative for disposing of Waste in Islamabad is uncontrolled landfilling. This dump site lacks a liner system and neither a leachate treatment nor a landfill gas collecting system is present. Composition diagram of scenario 1 is provided in figure 5.

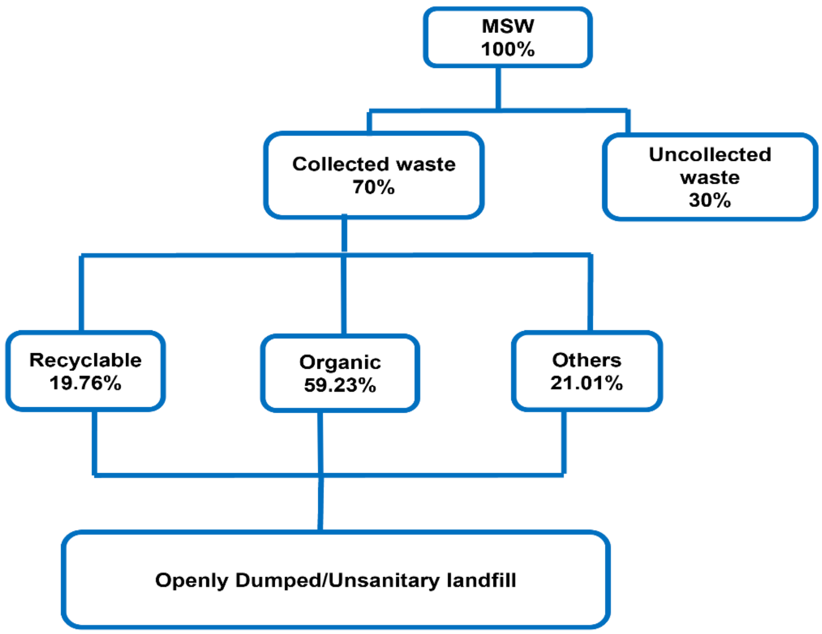


Figure 5: Composition Diagram for Scenario 1

3.3.3.2 Scenario 2: Sanitary Landfill with Recycling

In scenario 2, it is assumed that instead of the current dumpsite a sanitary landfill is built to dispose municipal solid waste. The recyclable content will be separated and recycled i-e 19.76%. Remaining 80.24%will be dumped into a sanitary landfill. Figure 6 presents the composition of scenario 2.

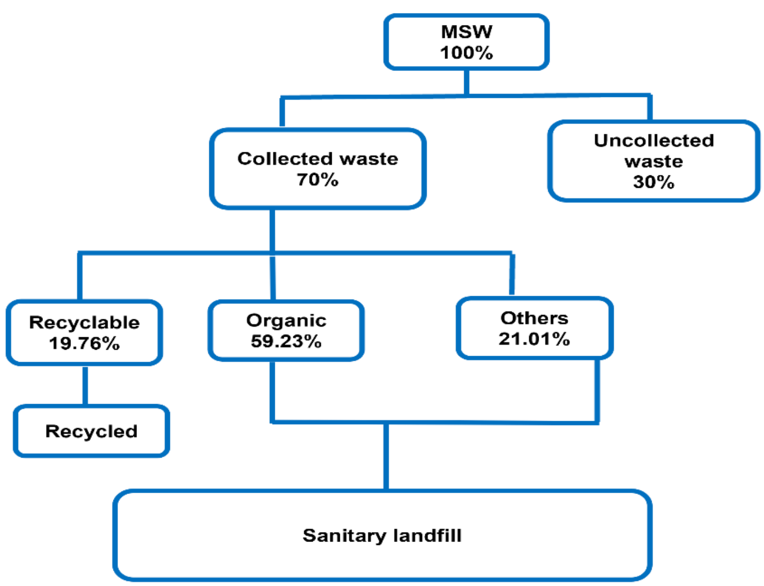


Figure 6: Composition Diagram for Scenario 2

3.3.3.3 Scenario 3: Anaerobic Digestion with Engineered Landfill

Recyclables are recycled in a material recycling facility i-e 19.76% of recyclables present in the municipal solid waste consisting of metal, plastic, rubber and glass. Organic fraction of waste is treated with anaerobic digestion i-e, 59.23%.

The remaining 20% will be disposed of in an engineered landfill. The biogas from anaerobic digestion is assumed to be collected at an efficiency rate of 55%. Figure 7 presents the composition of scenario 3.

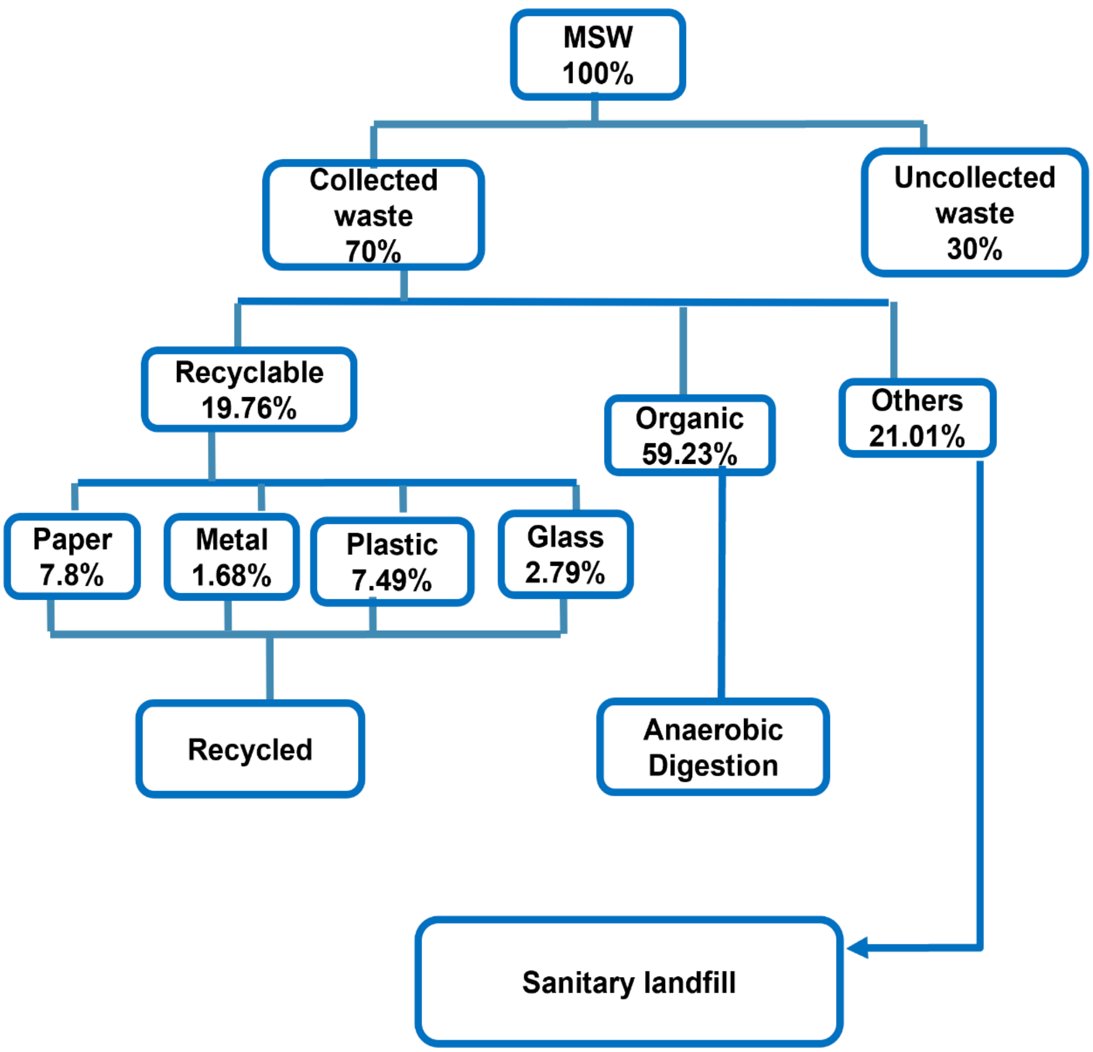


Figure 7: Composition Diagram for Scenario 3

3.3.3.4 Scenario 4: Composting Along with Engineered Landfill

Recyclables are recycled i-e 19.76% of the total municipal solid waste. Organic fraction of waste is treated with composting i-e, 59.2%.

Remaining 20% will be disposed of in an engineered landfill. Compost will be used as a soil enricher out of the end products of composting. Figure 8 presents the composition of scenario 4

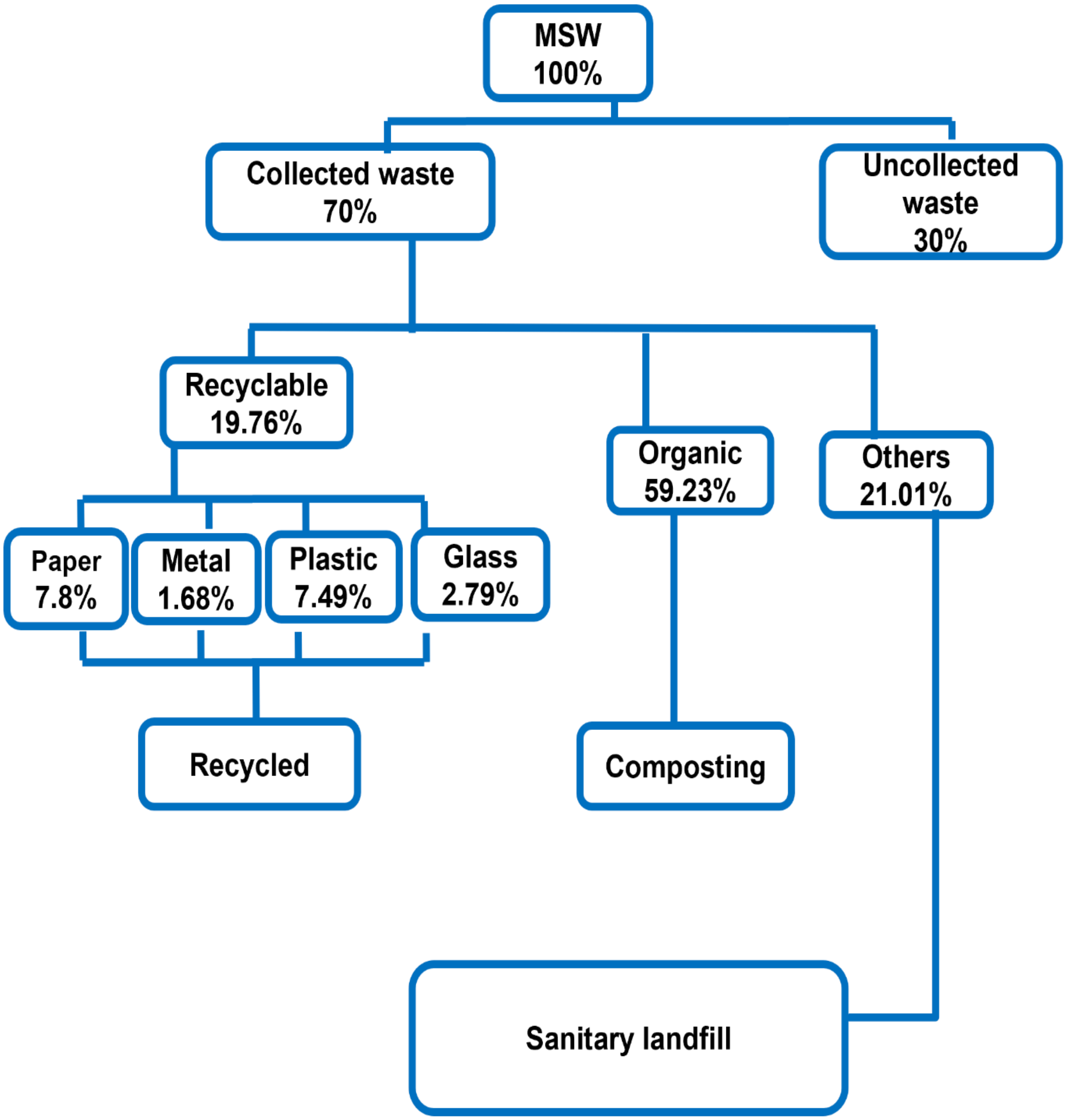


Figure 8: Composition Diagram for Scenario 4

3.3.3.5 Scenario 5: Incineration Along with Recycling

In this scenario it has been assumed that the recyclables are recycled i-e 19.76% in the Material Recycling Facility present while the remaining 80.24% of the waste is treated by the process of incineration. Figure 9 presents the composition of scenario 5.

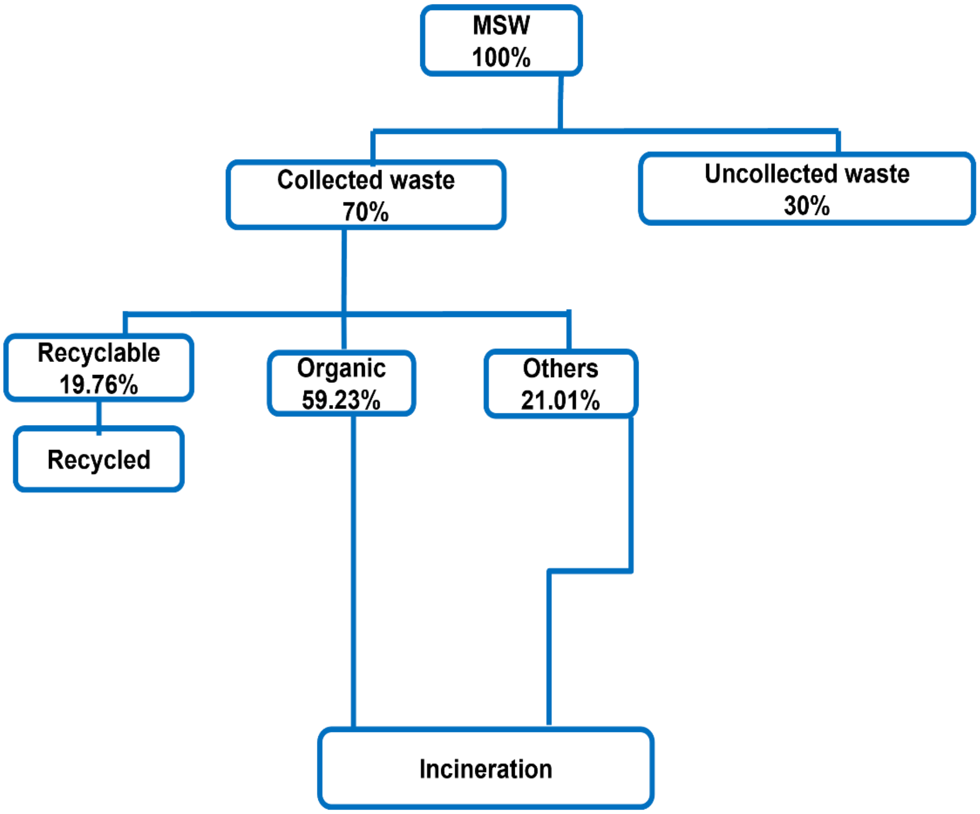


Figure 9: Composition Diagram for Scenario 5

3.3.4 Life Cycle Inventory

Reviews of the literature, surveys, and the Ecoinvent datasets included in the SimaPro library were the main sources of information for establishing the inventory. The Ecoinvent version 3.0 library within SimaPro was used to source detailed information about emissions to air and water, as well as thorough data about material and energy inputs and outputs for processes like transportation, electricity mix, unsanitary landfill, recycling, sanitary landfill, anaerobic digestion, industrial composting, and incineration.

3.3.5 Waste Composition for Life Cycle Assessment

In addition to potentially having a significant impact on the Life Cycle Assessment (LCA) of waste management systems, the composition of waste products does have a fundamental impact on environmental emissions linked to waste treatment, recycling, and disposal. Thus, the environmental efficacy of specific waste management systems may be immediately impacted by the waste composition.

The waste composition used in this study is from the waste amount characterization survey conducted in 2017 and the data has been provided by CDA. The composition is average of all seasons and high-, middle- and low-income levels. Table 4 presents the waste composition of municipal solid waste of Islamabad used in this study.

Table 4: waste composition of municipal solid waste of Islamabad

Sr. No	**Waste type**	**Percentage Composition (%)**
1	Paper	7.8
2	Glass	2.79
3	Ferrous metal	0.64
4	Nonferrous metals	1.04
5	Rigid plastic	3.11
6	Film plastic	4.38
7	Organic	59.23
8	Textile	1.81
9	Others	19.2
Total		100

3.3.6 Transport / Travel Distance of Current Management Facility

We have estimated the difference to be 16 kilometers on average as the point of collection of waste is assumed to be the same along with assuming that all the waste is then transported from that point of collection to the dumpsite in I-12. The transport distance considered in this study is 32 km as it has been calculated for the return trip of a vehicle that has a capacity of carrying 16 tons at a time.

3.3.7 Electricity/Heat Consumption in The Study

Electricity is also a system input that essentially determines the emissions and impacts of particular waste management scenarios on the environment. Pakistan is country where electricity generation is mostly dependent upon thermal sources followed by hydrological sources. Since the study has used system expansion approach, electricity has also been considered as an avoided product. Heat source used in this study is natural gas. Table 5 presents the electricity mix of Pakistan used in this study.

Table 5: Electricity mix of Pakistan

Type of energy generator	**Share in electricity generation**
Thermal	64%
Hydro	27%
Nuclear	7%
Renewable	2%

3.3.8 Material Inputs/Outputs for the Life Cycle Inventory

The material inputs and outputs data that has been calculated on the basis of data obtained from literature. The values used in creating the inventory of different processes to be used for developing scenarios for life cycle assessment are presented in table 6. The rest of data for all the inputs and outputs has been taken from Eco invent database, while where possible, the data was used which was available in the specific context of Pakistan.

Table 6: Inputs and outputs data used for modeling in SimaPro

Category	Parameter	Unit	Anaerobic Digestion	Composting	Sanitary Landfill	Incineration
Emissions to air	Biogenic CO_2	kg	210	220	139	751.5
	Hydrogen Sulfide	kg	0.089	0.52	-	-
	Ammonia	kg	-	0.7	0.08	0.69 (liquid)
Emissions to water	Nitrogen	kg	0.0001 (organic)	0.01 (total)	1.03 (long term)	0.01 (Nitrate)
	COD	kg	-	0.14	77.9 (long term)	0.4
Materials and energy input	Water	L	24	20	-	57
	Electricity/heat	kWh	66.9	11.8	3	-36.3 (heat)
	Diesel	L	2.5	2.5	-	-
	Oxygen	kg	-	100	-	1336
Materials output	Electricity	kWh	-	-	-	-385.87
	Wastewater	m^3	0.01	0.02	0.00004	0.01
Byproducts/avoided products	Compost/digestate	kg	620	500	-	-
	Biogas	m^3	114	-	114	-

3.3.9 Key Assumptions of the Present Study

In order to conduct the Life Cycle Assessment (LCA) for the present study, several assumptions were made in the life cycle inventory stage. The assumptions include the following:

1. Municipal solid waste collection: The rate of collection is assumed to be 700 tons per day.
2. Distance within the system boundary: The waste management options considered are within a distance of 16 km, with a round trip distance of 32 km.
3. Functional unit: The functional unit for the study is defined as 700 tons of waste.
4. Moisture content: The municipal solid waste is assumed to have an approximate moisture content of 58%.
5. Electricity mix: The assumed electricity mix comprises 64% thermal energy, 27% hydro energy, 7% nuclear energy, and 2% renewable energy sources.
6. Landfill area: The landfill area or dumping site covers an area of 0.186 km2.
7. Transportation mode: The transportation mode used is 16-ton lorries.
8. Composting plant: The waste management process includes a Windrow Composting plant for composting.
9. Anaerobic digestion: The anaerobic digestion process employs a Thermophilic single-stage digester.
10. Incinerator: The incinerator utilized is a grate incinerator equipped with an electrostatic precipitator for fly ash.
11. Long-term emissions: Long-term emissions have been considered for all waste management scenarios.
12. Spatial location: It is assumed that all waste treatment options are located within the same area.

These assumptions are important for conducting the life cycle assessment and establishing the boundaries and parameters of the study. They provide a basis for data collection and analysis, ensuring consistency and comparability throughout the assessment process.

3.3.10 Life Cycle Impact Assessment

The goal of the Life Cycle Impact Assessment (LCIA) phase, which is a crucial component of the LCA, is to comprehend and assess the scope and importance of any potential environmental effects of a process or product. The LCIA portion of this study used the CML-1A approach. The CML-1A methodology was created by the Centre of Environmental Science at Leiden University and offers a thorough approach, making it a preferred option for many researchers for evaluating environmental consequences across several categories. The eight categories chosen for evaluating the results of the selected scenarios are as follows:

1. Abiotic Depletion (fossil fuels)
2. Global Warming Potential (GWP100a)
3. Ozone Layer Depletion (ODP)
4. Human Toxicity
5. Freshwater Aquatic Ecotoxicity
6. Terrestrial Ecotoxicity
7. Acidification
8. Eutrophication

The selection of these eight indicators for our study was influenced by their applicability to waste management practices and by the significant environmental implications of these indicators available in LCA methodologies. These indicators accurately depict the main environmental issues caused by waste management, such as greenhouse gas emissions, the release of toxic substances, and the possibility of soil and water contamination. Additionally, concentrating on these indicators will enable a more concise and useful analysis, assisting policymakers in addressing the most urgent environmental problems connected to waste management in Islamabad.

3.3.11 Interpretation

Results from the Life Cycle Inventory and Life Cycle Impact Assessment will be systematically assessed during the interpretation phase. Decision-makers can benefit from the practical insights, which will guarantee that every conclusion is in line with the objectives and parameters established at the beginning. In the interpretation stage, we will evaluate our findings critically to identify Islamabad's most eco-friendly waste management plan. The effectiveness of each strategy will be evaluated in terms of its overall environmental impact, highlighting both problematic areas and promising areas for improvement. The interpretation stage of the life cycle assessment also includes a sensitivity analysis as one of its components. The reliability of the LCA results in the future depends heavily on this step. By varying an input parameter within specific ranges responsiveness and robustness of our anticipated results has been evaluated. The sensitivity analysis makes it easier to spot any potential uncertainties and the important factors that could significantly affect the results.

4. RESULTS AND DISCUSSION

This chapter summarizes the outcomes of the data analysis and offers a thorough analysis and discussion of these findings. The research objectives and questions specified in the study are to be addressed in this chapter. Utilizing the relevant tables, figures, and statistical analysis, the results are presented in an understandable and structured manner. This chapter provides insights, explanations, and possible directions for further study through a thorough analysis and interpretation of the findings.

4.1. Life Cycle Impact Assessment of the Modelled Scenarios

The study examined and assessed Islamabad city's existing solid waste management issue in order to determine a environmental friendly option and review the existing waste management technique. On the basis of field data analysis and departmental data analysis, the current waste collection, transportation, and disposal of were determined and analyzed. The outcomes of the environmental impact assessment show the environmental impacts of eight different impact categories across five waste management scenarios. The results have been taken in terms of characterization values taken from CML-1A baseline method. Table 7 presents the characterization indicators used for life cycle impact assessment analysis in this study.

Table 7: Characterization indicators used for the study

Sr. no	**Characterization value**	**Unit**
1	Abiotic depletion (fossil fuels)	MJ
2	Global warming (GWP100a)	kg CO2 eq
3	Ozone layer depletion (ODP)	kg CFC-11 eq
4	Human toxicity	kg 1,4-DB eq
5	Fresh water aquatic ecotox.	kg 1,4-DB eq
6	Terrestrial ecotoxicity	kg 1,4-DB eq
7	Acidification	kg SO2 eq
8	Eutrophication	kg PO4--- eq

Abiotic depletion (fossil fuels)

Lower Heating Value (LHV), which is represented as MJ per kg of fossil fuel in m^3, is correlated with abiotic depletion of fossil fuels. The use of the LHV is justified since fossil fuels are viewed as completely substitutable.

Global warming (GWP100a)

It relates to greenhouse gas emissions to the atmosphere. A 100-year time horizon (GWP100) is used to calculate the global warming potential.

Ozone layer depletion (ODP)

The potential for ozone depletion brought on by different chemicals is presented under this category. It evaluates how these gases affect the ozone layer's deterioration, which is essential for shielding the planet from dangerous UV radiation.

Human toxicity

This category focuses on how harmful chemicals affect the environment around people. It defines how harmful compounds behave, are exposed to, and their fate in the long term on the humans.

Fresh water Ecotoxicity

The indicator assesses the effects of hazardous chemical emissions on freshwater ecosystems in the air, water, and soil. It evaluates the possible consequences of these emissions on the wellbeing and stability of aquatic life as well as the general ecological harmony of freshwater systems.

Terrestrial ecotoxicity

Terrestrial ecotoxicity is a category used to evaluate the possible impact of hazardous chemicals on ecosystems on land. It takes into account how these compounds interact with animals and ecological systems in terrestrial habitats and how they are exposed to them.

Acidification

The fate and deposition of acidifying chemicals including hydrogen sulfide, nitric oxide, hydrogen chloride and other chemicals are discussed in relation to emissions to the air under this midpoint category.

Eutrophication

This midpoint category includes all effects brought on by the overabundance of macronutrients in the ecosystem as a result of nutrient emissions to the air, water, and soil.

Figure 10 presents the waste management scenario alternatives that were taken into consideration for Islamabad. Five scenarios were modelled after the analysis of four waste management options. Scenario 1 reflects the current situation, in which all waste is delivered to an open waste dumping site. In Scenario 2, there is a sanitary landfill alternative, in which 80.24 % of the waste is disposed of in a sanitary landfill and 19.76 % is recycled. In Scenario 3, which focuses on anaerobic digestion (AD), 21.01% of the waste is transferred to a sanitary landfill, 59.23% of it is anaerobically digested, and 19.76% is recycled. In Scenario 4, which examines composting, 19.76% of the waste is recycled, 59.23% is composted commercially, and 21.01% is disposed of in a sanitary landfill. Scenario 5 also takes into account incineration, with 19.76% recycled and 80.24% handled by incineration. Byproducts of the sanitary landfill, anaerobic digestion and composting is assumed to be utilized and thus assumed as avoided product. The waste treatment area is assumed to be located 16km away from the collection point of the municipal solid waste from where the system boundary starts. The transport distance assumed is for a return trip and thus 32 km transport process was modelled in this scenario for transporting 700 tons of municipal solid waste on a daily basis. For transportation of the municipal solid waste, 16 tons mini dumpers are assumed to be used. All the sorted-out fractions received from the collected municipal solid waste operations from neighborhoods within all various times were combined in order to reduce the complexity of modeling MRF in SimaPro. This presumption led to the conclusion that scavengers' sifting at dumping site, anaerobic digestion, incineration, and decomposition was minimal.

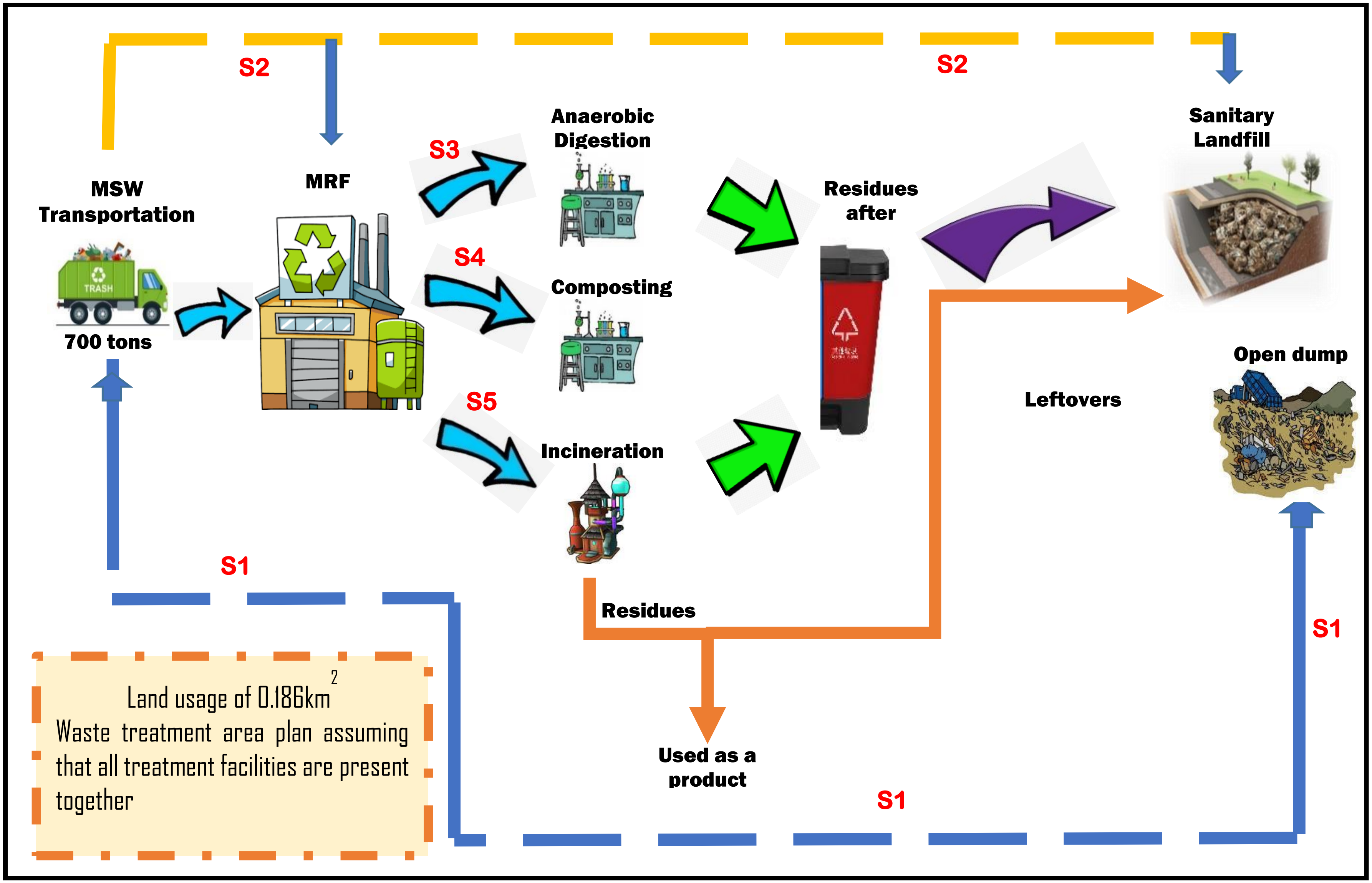


Figure 10: Current Assumed Solid Waste Management Scenario in Islamabad

4.1.1 Life Cycle Impact Assessment of Scenario 1

Islamabad produced 1,000 tons of waste in total. Scavenging and other unofficial recycling methods weren't included in the calculation of this quantity, which was based on government data on waste collection. The currently used unregulated landfill or open dumpsite received 100% of the MSW that was gathered and dumped there. It should be emphasized that in this situation there is no refuse recycling or energy recovery. Furthermore, the present waste disposal lacks a system for gathering and processing leachate to safeguard the aquifer, and neither gas collection nor flaring was taken into consideration.

S1 was modelled as a business-as-usual scenario for Islamabad's waste management. According to sources from Capital Development Authority, more than 95% of Islamabad solid waste is directly sent for open dumping. The current site for open dumping of municipal solid waste is I-12 which is being shifted to H-16 Islamabad now. Open dumping is the practice of disposing of solid wastes on land in a way that does not safeguard the ecosystem, exposes the refuse to the weather, vectors, and scavengers, and leaves it vulnerable to open burning. Thus all these contribute to its negative impacts.

The characterization results give an in-depth view of the environmental burdens of the scenarios modelled and quantify environmental indicator for better understanding. The highest impacted categories are Abiotic depletion of fossil fuels, Global Warming Potential, Human Toxicity, Freshwater Aquatic Eco toxicity. The waste decomposes anaerobically, producing methane, a powerful greenhouse gas. Toxic liquid leachate is created when refuse interacts with rainfall and wetness created during the decomposition process thus, contributing to higher values in these categories. Talang & Sirivithayapakorn (2021), who also identified untreated leachate as the main component of unsanitary and sanitary landfills for environmental caused by open dumping(Prateep Na Talang and Sirivithayapakorn 2021).

Table 8 presents the overall contribution of processes in scenario 1. Since the transport process contribution in this scenario is almost negligible, the transport process effects in the life cycle impact characterization results are negligible. This is because the effect of current practice for municipal solid waste management in Islamabad i-e, Open dumping has far more greater impacts as compared to the transportation process.

Table 8: Scenario 1 Life Cycle Impact Assessment characterization results for processes

Impact category	**Unit**	**Transport process 32KM**	**MSW Open-dumping**
Abiotic depletion (fossil fuels)	MJ	152	43,741
Global warming (GWP100a)	kg CO_2 eq	11	803,348
Ozone layer depletion (ODP)	kg CFC-11 eq	0.0000019	0.00054
Human toxicity	kg 1,4-DB eq	2.8	122,131
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	0.8	1,367,171
Terrestrial ecotoxicity	kg 1,4-DB eq	0.004	963
Acidification	kg SO_2 eq	0.05	45
Eutrophication	kg PO_4 eq	0.01	5,171

4.1.2 Life Cycle Impact Assessment of Scenario 2

To determine the effects of converting Islamabad's existing waste into a sanitary landfill without a methane collection system Scenario (SC2) was developed. To protect groundwater from any contamination brought on by landfill runoff, leachate gathering, and treatment systems are implemented. In this case landfill gas recovery and its conversion to energy was considered. The significant environmental effects of sanitary landfills, particularly on GWP and Freshwater Aquatic Ecotoxicity, were highlighted by HePing et al. (2018). It's interesting to note that their research also offered the possibility of possible mitigation methods by reducing the potential values of various environmental impact indicators through the distribution of surplus electricity produced as a by-product. This information adds to the trends our analysis revealed(HePing et al. 2018).

Without significant changes to the infrastructure, this landfill got the same volume of waste as in the baseline case (SC1), straight from mixed municipal waste transfer stations. Therefore, this method still needed almost the same amount of space for the landfilling procedure as the present waste management.

In this scenario, it was assumed that the recyclable portion of the municipal solid waste that constitutes of 19.76% of the total collected municipal solid waste is recycled while the rest 80.24% is sent to a sanitary landfill. Recyclables constitute of 7.8% paper, 7.49% plastic, 1.68% metal and 2.79% glass. The transport distance for sanitary landfill was considered same as baseline scenario i-e, 32km for a round trip.

Table 9: Scenario 2 characterization results for processes

Impact category	**Unit**	**Transport Process**	**Sanitary Landfill Process**	**Recycling Process**
Abiotic depletion (fossil fuels)	MJ	152	149,935	646,915
Global warming (GWP100a)	kg CO_2 eq	11	349,724	-54,290
Ozone layer depletion (ODP)	kg CFC-11 eq	0.0000019	0.0016	0.0012
Human toxicity	kg 1,4-DB eq	2.8	107,433	-42,766
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	0.8	1,091,796	-71,347
Terrestrial ecotoxicity	kg 1,4-DB eq	0.004	782	-1,503
Acidification	kg SO_2 eq	0.05	63	-641
Eutrophication	kg PO_4 eq	0.01	1,430	-454

In S2, 19.7% of waste is recycled and the rest is sent to a sanitary landfill without any treatment. Modern engineering landfills enable refuse to decompose into chemically and biologically inert materials in a setting that is separated from the environment and hence significantly undamaging to the environment. The characterization values for S2 are presented in Table 9. The main contributor to environmental burdens in case of S2 is sanitary landfill process. Recycling process depicts Abiotic Depletion Potential due to presence of Material Recycling Facility (MRF).

A net saving in terms of Global Warming Potential could be observed if landfill gas collection is introduced. Landfills emit Methane and as no methane recovery option is available the Global Warming Potential of this process is positive. The evaluation of transport process indicates that the values are negligible due to a higher positive impact generated by sanitary landfill process and saving caused by the recycling process. Except for Abiotic Depletion Potential as well Ozone Depletion Potential, all other indicator results show environmental benefits in terms of waste recycling process.

4.1.3 Life Cycle Impact Assessment of Scenario 3

Anaerobic digestion (AD), a method of treating biodegradable municipal solid waste is a technique in which organic refuse is sent to decompose in the lack of oxygen to produce digestate, a stabilized byproduct and biogas. Wet and dry methods can be eminent in digestion technology. The dry technique, which can use municipal solid waste as a major input for the digestion process, is usually run with 25 to 40 percent total solids (TS). A water volume of 10% to 15% of the overall solid is used when performing the wet process. Moreover, either thermophilic or mesophilic settings are used to carry out the digestion procedure. Due to the benefits of quicker decomposition, pathogen eradication, and a higher methane output thermophilic process comprising single stage digestion with post composting was modelled.

In this case, it was assumed that only 19.76% of the city solid refuse gathered which was recyclable was recycled and the remaining 80.24 percent was disposed of in a sanitary landfill. Paper, plastic, metal, and glass make up the majority of recyclables at 7.8%, 7.49%, 1.68% and 2.79 % respectively. In this situation, the transit distance for municipal solid waste to treatment site and sanitary landfill was assumed to be 32 km roundtrip. The treatment of organic waste through anaerobic digestion entails a number of biological procedures in which microorganisms break down organic refuse in the lack of oxygen. Biogas is the final byproduct of the process.

The production of beneficial gas, liquid, and fibrous fertilizers by anaerobic digestion are some of the most remarkable facts about it along with its ability to greatly reduce GHG emissions. In addition to process emissions and the necessary plant equipment, the energy requirement for running an anaerobic treatment plant was considered. SimaPro's library of anaerobic digestion technology was used for the simulation, and Pakistan-specific inputs were chosen. The system is thermophile, single stage digestion with post composting. Biogas collection of 114m^3 per ton of waste was included as part of the process. The characterization results of Scenario 3 modelled for municipal solid waste of Islamabad are presented in table 10.

Table 10: Scenario 3 characterization results for processes

Impact category	**Unit**	**Transport process 32km**	**Recycling**	**Anaerobic Digestion**	**Sanitary Landfill**
Abiotic depletion (fossil fuels)	MJ	152	646,915	5,432	39,278
Global warming (GWP100a)	kg CO_2 eq	11	-54,290	-84,768	91,617
Ozone layer depletion (ODP)	kg CFC-11 eq	0.0000019	0.0012	-0.0091	0.00041
Human toxicity	kg 1,4-DB eq	2.8	-42,766	-94,835	28,144
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	0.8	-71,347	-228,992	286,017
Terrestrial ecotoxicity	kg 1,4-DB eq	0.004	-1,503	-503	205
Acidification	kg SO_2 eq	0.05	-641	-489	16.5
Eutrophication	kg PO_4 eq	0.01	-454	-1,643	375

Scenario analysis of S3 shows that AD of organic fraction of municipal solid waste demonstrates environmental improvements in terms of most of environmental indicators generating a merely significant impact for categories such as ADP and MAE. Anaerobic Digestion (AD), according to Mayer et al. (2021), has less of an impact on the ozone layer's depletion. In comparison to directly incinerating Organic Fraction of Municipal Solid Waste (OFMSW), the NOx emissions from biogas combustion are lower(Mayer, Bhandari, and Gäth 2021). Normalization results indicate FWAE and MAE as significant indicators for evaluating this scenario.

4.1.4 Life Cycle Impact Assessment of Scenario 4

Scenario 4 has been designed as a process where the organic fraction of waste is treated with composting i-e, 59.2% Remaining, Recyclables are recycled i-e 19.76% and the remaining 20% will be disposed of in an engineered landfill. Compost will be used as a soil enricher out of the end products of composting. There are many environmental benefits of composting leftover food and other organic waste, including improving soil health, decreasing emissions of greenhouse gases and recycling minerals from the organic part of the solid waste. Paper, plastic, metal, and glass make up the majority of recyclables at 7.8%, 7.49%, 1.68% and 2.79 % respectively. For this scenario, a 32 km total travel route was taken as well since it has been assumed in the study that all the waste treatment facilities are present at site.

Composting simply creates the ideal environment to hasten the breakdown process atmosphere for bacteria, fungus, and other decomposing organisms (nematodes, sowbugs, and worms) to carry out their functions. All that grows eventually breaks down. The resultant decomposed substance, which frequently mimics healthy yard soil, is referred to as compost. Compost is nutrient-rich and useful and is demonstratively referred to by farms as "black treasure" used in gardening, agriculture and farming.

The process of composting has many benefits that include the reduction in greenhouse gas emissions from the landfills since the process of anaerobic digestion starts in landfills and thus biogas is produced as a byproduct which contains greenhouse gases. Composting ensures that the nutrients taken out from soils in the form of food is returned to the soil in the form of soil enriching compost. Since compost is a source of organic nutrients, it also increases the soils ability to retain water.

When applied to soil, compost has positive effects. it is a humified solid particulate product of decomposition that has been cleaned up and fixed and has positive effects. It functions as a component of growing soil or in another manner in combination with plants. The process modelled describes industrial composting. Energy required for functioning of a compost plant was encompassed as well as process emissions and the input emissions from establishment of the infrastructure of the compost plant. The characterization results of Scenario 3 modelled for municipal solid waste of Islamabad are presented in table 11.

Table 11: Scenario 4 characterization results for processes

Impact category	**Unit**	**Transport process 32km**	**Recycling**	**Biowaste, Composting**	**Sanitary Landfill**
Abiotic depletion (fossil fuels)	MJ	152	646,915	-42,836	39,278
Global warming (GWP100a)	kg CO_2 eq	11	-54,290	-2,655	91,617
Ozone layer depletion (ODP)	kg CFC-11 eq	0.0000019	0.0012	-0.00023	0.00041
Human toxicity	kg 1,4-DB eq	2.8	-42,766	-49,083	28,144
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	0.8	-71,347	-31,890	286,017
Terrestrial ecotoxicity	kg 1,4-DB eq	0.004	-1,503	-12.9	205
Acidification	kg SO_2 eq	0.05	-641	601	16.5
Eutrophication	kg PO_4 eq	0.01	-454	65	375

The high nitrogen emissions due to the composting process result in higher positive values for acidification and eutrophication indicators. Because biogenic CO_2 is not regarded to be a significant contributor to global warming, the composting procedure has little impact on the global warming potential indicator findings(Edwards et al. 2017). The analysis depicts the highest impact on Freshwater aquatic Eco toxicity followed by anaerobic digestion and Global Warming Potential. The results show an Environmental benefit in case of Terrestrial Eco toxicity, Human Toxicity as well as Acidification and Eutrophication generated by the anaerobic digestion process in this scenario. The emissions from the transport process are negligible when process contributions in the scenario are comprehended.

High acidification values are brought on by the emission of acidifying compounds like NOx and SOx, with NOx having a greater acidification impact than SOx. The studies conducted by (Mali and Patil 2016) in India, (Ogundipe FO and Jimoh OD 2015)in Nigeria, (Yadav and Samadder 2018) in India, and (Erses Yay 2015) in Turkey all support the idea that potential impacts of the composting can be reduced when proper sorting and material recovery are done along with composting of biodegradable waste and landfilling of the residues (S2).

4.1.5 Life Cycle Impact Assessment of Scenario 5

The thermal waste management technique of incineration can be assumed of as a controlled combustion procedure with the main goals of refuse stream volume decrease and energy recovery. The most common method for converting waste into energy is incineration, which allows for the recovery and conversion of combustion-generated heat into electric power. The organic component of refuse consumes and produces heat, whereas the inorganic component of waste contributes to the production of ash. Aside from debris, incineration also produces heat and combustion fumes.

Assumptions made for the burning process include typical Swiss MSWI facilities (grate incinerators) with moist flue gas scrubbers and electrostatic precipitators for fly ash (ESP). This refuse breaks down into 0.02224 kg of leftovers and 0.2221 kg of slag per kilogram, both of which are landfilled.

The characterization results for analysis of Scenario 5 including incineration of 80% of waste along with recycling of the 19.76% of recyclables is as shown. There is a trend of net saving for Scenario 5 In spite of the fact that lignite, hard coal, and natural gas are all consumed during incineration to produce energy (Erses Yay 2015). Due to the decrease in pollution made feasible by substituting recovered materials for raw materials, recycling results in savings in each scenario. Due to the lack of available data, downstream emission in landfill sites was not considered. The characterization results of Scenario 5 modelled for municipal solid waste of Islamabad are presented in table 12.

Table 12: Scenario 5 characterization results for processes

Impact category	**Unit**	**Transport process 32KM**	**Recycling**	**Incineration**
Abiotic depletion (fossil fuels)	MJ	152	646,915	-1,541
Global warming (GWP100a)	kg CO_2 eq	11	-54,290	158
Ozone layer depletion (ODP)	kg CFC-11 eq	0.0000019	0.0012	-0.000019
Human toxicity	kg 1,4-DB eq	2.8	-42,766	3,516
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	0.8	-71,347	23,196
Terrestrial ecotoxicity	kg 1,4-DB eq	0.004	-1,503	0.22
Acidification	kg SO_2 eq	0.05	-641	-0.42
Eutrophication	kg PO_4 eq	0.01	-454	0.008

Even though incineration requires fossil fuels like hard coal, natural gas, and lignite for energy production, there is a trend toward net positive savings. In Scenario 5 the highest impact is on Anaerobic Depletion followed by Ozone depletion. Analysis shows environmental benefits in case of Global Warming Potential and Freshwater Aquatic Eco toxicity. The potential advantages of contemporary incineration techniques were also highlighted by Anshassi et al. in 2021. Their research underlined the significance of effective energy recovery from waste combustion, pointing out that it can reduce greenhouse gas emissions from sources of energy that typically emit them. The study emphasized that incineration can be a beneficial method from a GHG emission perspective when taking into account the direct reduction in raw material extraction and processing, as well as effective post-combustion treatment measures(Anshassi, Sackles, and Townsend 2021).

4.2. Comparison of the Modelled Scenarios

Due to the usage of fossil fuels such as hard coal, natural gas, and lignite for power, Scenario 5 has the greatest effect on abiotic depletion. Methane is the primary source of global warming in the landfilling alternatives (S1 and S2), and since there is no emission control mechanism in place, methane is also released into the atmosphere directly. In Scenario 3, the avoidance of carbon dioxide and nitrogen monoxide emissions caused by the production of manure and fertilizer has a favorable effect on the potential for global warming.

Municipal waste landfilling is regarded as the least environmentally friendly technique of the suggested waste management practices, as it has already been documented in the literature. This is due to the substantial negative impacts that this process has on both freshwater toxicity as well as on human health.

In terms of terrestrial Eco toxicity all scenarios except baseline scenario i-e, scenario 1 showed net benefit. Landfilling causes the most adverse impact on freshwater aquatic eco toxicity due to methane emissions as a resultant of the biogas production during the course of landfilling. The best results are achieved in Scenario 3 i-e, the combination of a composting process for organic fraction along with recycling of the organic fraction and the rest of the waste being sent to a sanitary landfill.

The amount of H+ ions generated per kilogram of a material in relation to SO_2 is what is known as the acidification potential (Bauman and Tillman, 2004). SO_2, NOx, HCl, and NH_3 are the principal acidifying contaminants. The acidification potential of the business as usual scenario is the highest among all others due to excessive emissions of CO_2 gas as a byproduct of biogas emissions particularly from the organic fraction of the municipal solid waste. The similar case is of the eutrophication indicator. Life cycle assessment of the baseline scenario (S1) is helpful in supplementing the life cycle database for Islamabad at present.

All the alternative scenarios modelled for comparison in the study lead to a significant reduction in airborne and waterborne emissions compared to Scenario 1. There is a net saving during processes due to avoided products and the advantage of not using virgin materials during the production of plastics, metals, glass and paper due to the recycling process. The input provided by waste collection, waste transportation to transfer stations, and treatment facility construction is negligible in each scenario as all other processes have significant contributions to the scenario that make the transport process seem negligible.

Normalization values indicate that marine aquatic, freshwater aquatic, terrestrial ecotoxicity and global warming are the most significant impact categories that need to be considered for municipal solid waste management alternatives. Additionally, it appears that waste incineration has both benefits and drawbacks. The primary issues of incineration are the substantial amounts of gaseous pollutants as well as the lingering dangerous waste materials which demand stringent air pollution control and secure dispersal and disposal.

The need to build a landfill is unavoidable in all situations for the removal of all refuse parts that are unable to be valorized, it is essential to note that there is significant possibility for the production of energy from urban waste, landfill gas, and occasionally anaerobic digestion of segregated waste which needs to be explored further. Table 13 presents overall values for all waste scenarios assumed in this study and the comparison of environmental indicators selected for comparison for each scenario separately.

The Life Cycle Assessment (LCA) of various scenarios to compare the municipal solid waste management (MSWM) choices for Islamabad city that have the least negative environmental effects is presented in the table. Almost all environmental indicators showed that Scenario 1 (S1) had the greatest environmental impacts, followed by Scenario 2 (S2). Because long-term emissions were taken into account in the study, the results for freshwater ecotoxicity (FWE) and human toxicity (HT) in these scenarios were much higher. Particularly, it was discovered that in Islamabad, the short-term emissions of FWE for scenario 1 were 6.67 kg 1,4-DB eq for 1 ton of municipal solid waste (MSW).

In contrast, scenario 3 (S3) showed net environmental savings for all evaluated environmental indicators with the exception of abiotic fossil fuel depletion. The Material Recovery Facility (MRF) used in the recycling process is to be primarily accountable for this outlier. Overall, the comparison shows each scenario's environmental performance and thus emphasizes the significance of taking into account long-term emissions and the function of certain waste management system activities.

Anaerobic digestion has been shown to have both environmental and financial benefits when used to treat municipal solid waste. Anaerobic digestion and pyrolysis can work together to maximize waste treatment efficiency and minimize environmental burdens, according to a thorough life cycle assessment by (Wang et al. 2021). Furthermore, Demichelis et al., 's research on the life cycle assessment and costing of advanced anaerobic digestion of organic municipal solid waste highlighted the technique's advantages in terms of both the environment and the economy further supporting the idea that anaerobic digestion is the most advantageous option for municipal solid waste(Demichelis et al. 2022).

Table 13:Characterization results for scenario comparison for all scenarios

Impact category	Unit	SC 1	SC 2	SC 3	SC 4	SC 5
Abiotic depletion (fossil fuels)	MJ	43,893	797,004	690,077	643,510	645,526
Global warming (GWP100a)	kg CO2 eq	803,359	295,445	-51,398	34,682	-54,120
Ozone layer depletion (ODP)	kg CFC-11 eq	0.001	0.003	-0.007	0.001	0.001
Human toxicity	kg 1,4-DB eq	122,134	64,670	-110,673	-63,702	-39,246
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	1,367,171	1,020,448	-26,709	182,780	-48,150
Terrestrial ecotoxicity	kg 1,4-DB eq	963	-721	-1,811	-1,311	-1,503
Acidification	kg SO2 eq	46	-578	-1,115	-23	-641
Eutrophication	kg PO4--- eq	5,171	976	-1,739	-14	-454

4.3. Scenario Comparison for each Environmental Indicator

Among the 8 selected midpoint indicators for assessing the environmental impacts of the selected municipal solid waste management scenarios, each scenario performed differently for each impact category due to the involved factors such as the current situation of waste management, avoided products and utilized inputs and outputs of each scenario.

4.3.1. Scenario Comparison for Abiotic Depletion of Fossil Fuels

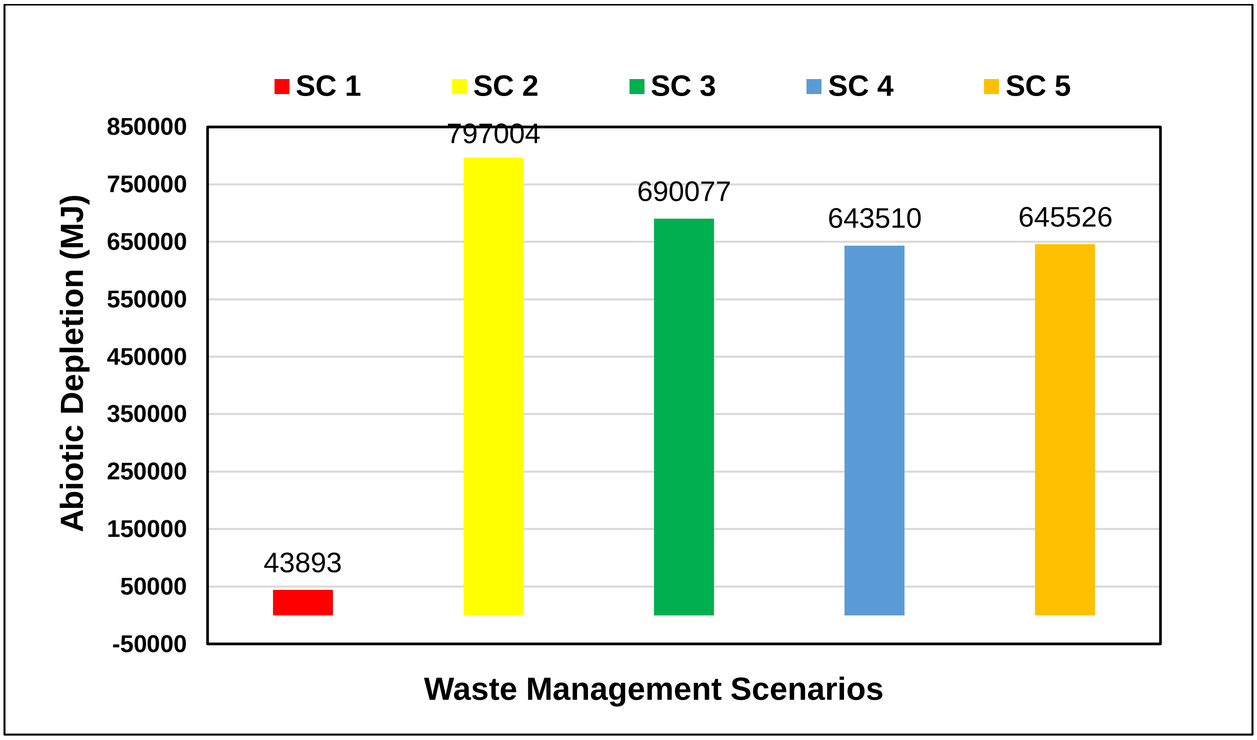


Figure 11: Scenario Comparison for Abiotic Depletion of Fossil Fuels

Assessing the best environmentally friendly option for municipal solid waste management (MSWM) involved comparing the five modelled scenarios. Because a sanitary landfill was present and there were no ecologically friendly operations, Scenario 2 (Sanitary landfill) had the largest potential for abiotic depletion as presented in figure 11. The Unsanitary landfill scenario, which didn't feature any activities that used fossil fuels, however, had the lowest environmental burden in terms of abiotic depletion of fossil fuels. For 700 tons of municipal solid waste of Islamabad, Sc 2 has 797,004 MJ of abiotic depletion of fossil fuels followed by scenario 3, 5 and 4 with scenario 1 having the least value of 43,893 MJ.

4.3.2. Scenario Comparison for Global Warming Potential (GWP 100a)

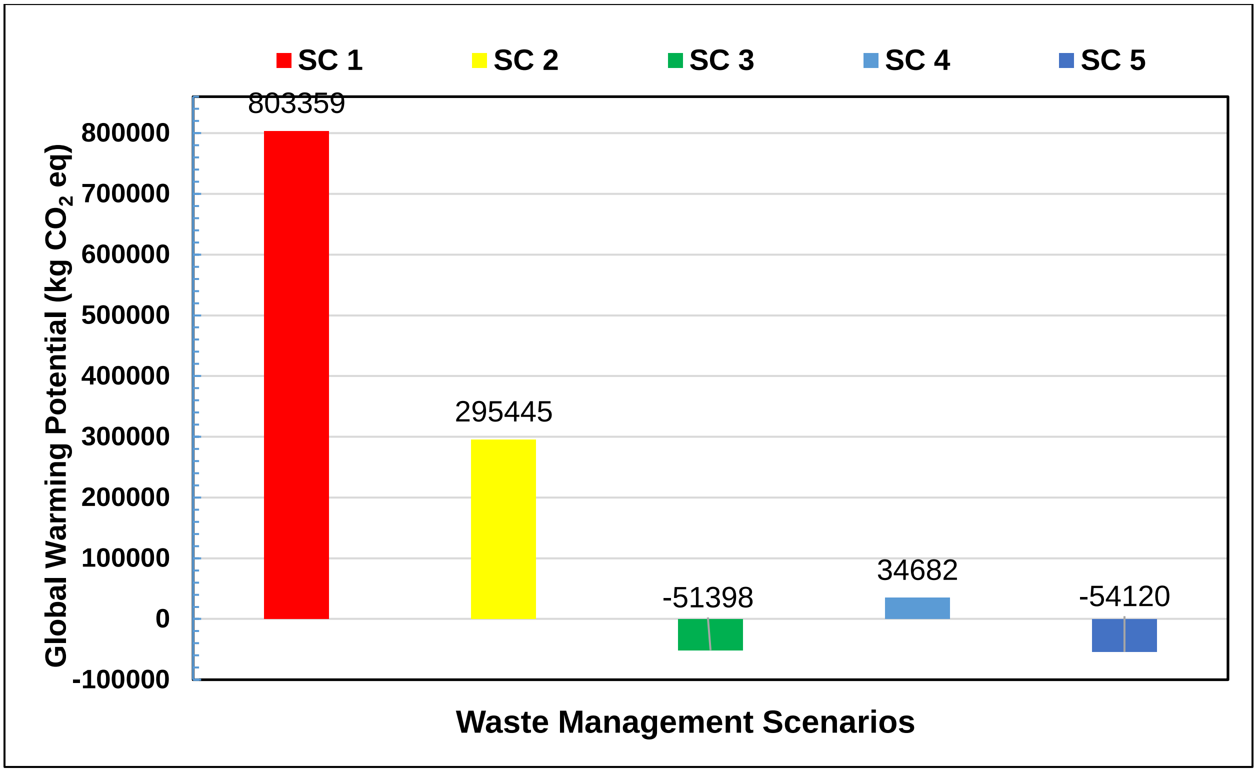


Figure 12: Scenario Comparison for Global Warming Potential (GWP 100a)

Due to the considerable methane emission brought on by the breakdown of organic waste, Scenario 1 (Unsanitary landfill) showed the largest environmental impact in terms of Global Warming Potential (GWP). On the other hand, incineration displayed a reduced GWP as a result of the waste being burned, which lowers methane emissions and uses energy. In contrast to unsanitary landfilling, incineration may still generate greenhouse gases, but at a lesser pace, which contributes to a comparatively lower GWP. For the GWP metric, anaerobic digestion (AD) and incineration both demonstrated environmental savings. With its capacity to recover energy, the incineration process limits the release of methane and lowers net greenhouse gas emissions.

Similar to this, Anaerobic Digestion, which includes the decomposition of organic waste in an atmosphere with limited oxygen, also stops the emission of methane and so adds to environmental savings in terms of GWP. These results highlight the significance of adopting waste management techniques that prioritize lowering methane emissions, including AD and incineration, to lessen the impact of MSWM on global warming. The results of Global Warming Potential of each scenario compared with one another is presented in figure 12.

4.3.3. Scenario Comparison for Ozone Layer Depletion

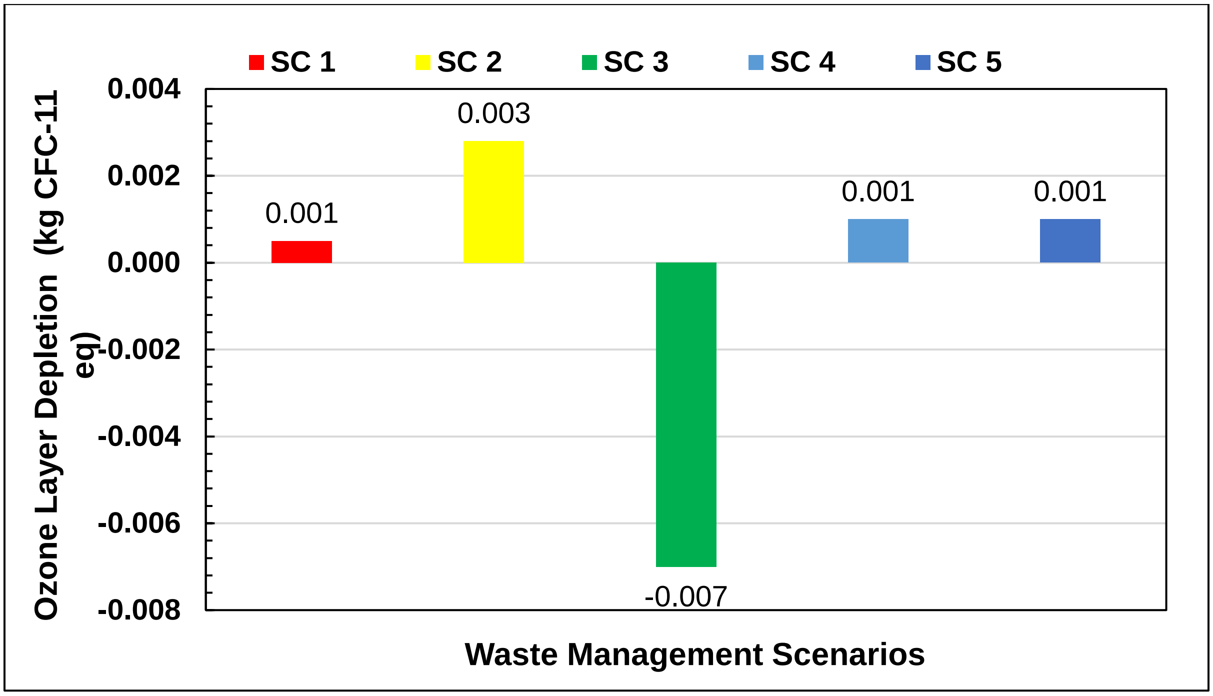


Figure 13:.Scenario Comparison for Ozone Layer Depletion

Because of the gases like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) that are released from waste that is landfilled, the sanitary landfill scenario showed a larger potential for ozone layer depletion in terms of ODP. On the other hand, because anaerobic digestion scenarios often do not entail the production of ozone-depleting chemicals, they showed the greatest environmental savings. Therefore, compared to situations requiring sanitary landfilling, anaerobic digestion procedures have a lesser risk for ozone layer depletion. The highest impact was shown by scenario 2 for which the value of ODP was 0.003 CFC-11 eq as compared to scenario 3, which showed environmental savings with an ODP value of -0.007 CFC-11 eq. The comparison of all scenarios is presented in figure 13.

These results underline how important waste management techniques are in determining the likelihood of ozone layer ozone layer depletion. Anaerobic digestion procedures serve as an example of how to avoid compounds that deplete the ozone layer and offer an ecologically friendly option to reduce the effect on the ozone layer. Incorporation of such practices into municipal solid waste management strategies in Islamabad can contribute to sustainable waste treatment and minimize the potential for ozone layer depletion.

4.3.4. Scenario Comparison for Human Toxicity

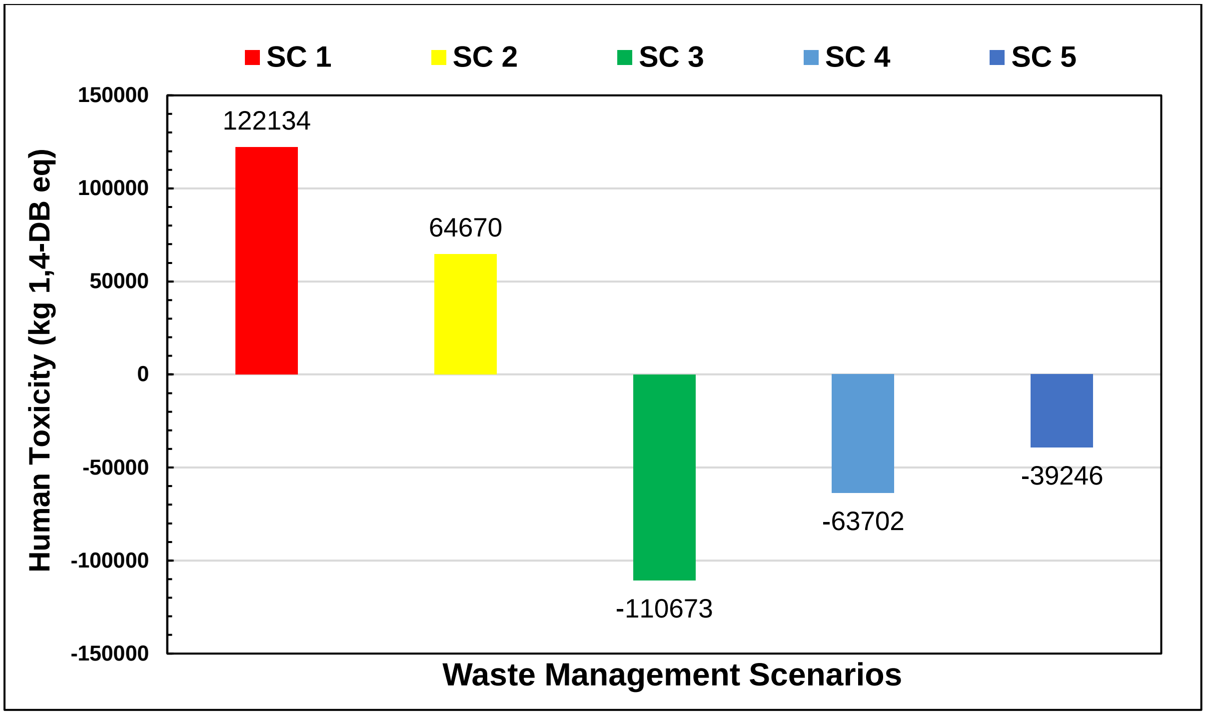


Figure 14: Scenario Comparison for Human Toxicity Potential

Human toxicity as presented in figure 14, is higher in unsanitary landfill environments than in other waste management options. Leachate, which is produced during the operation of unsanitary landfills , releases harmful compounds into the environment and can damage soil and water supplies. Through direct contact or tainted food and water sources, these toxins can be harmful to human health. Anaerobic digestion procedures, in contrast, frequently entail controlled and regulated circumstances that limit the release of hazardous chemicals. Therefore, scenarios involving anaerobic digestion show environmental savings with human toxicity potential value of -110,673 1,4-DB eq in terms of possible human toxicity.

Anaerobic digestion is managed, which serves to lessen the overall influence on human health and any threats brought on by harmful chemicals. These results highlight the significance of adopting waste management techniques like anaerobic digestion that prioritize the control and reduction of harmful chemical discharge. By doing this, the potential threats to human health may be successfully reduced, resulting in waste management practices that are more ecologically friendly and sustainable.

4.3.5. Scenario Comparison for Fresh Water Aquatic Ecotoxicity

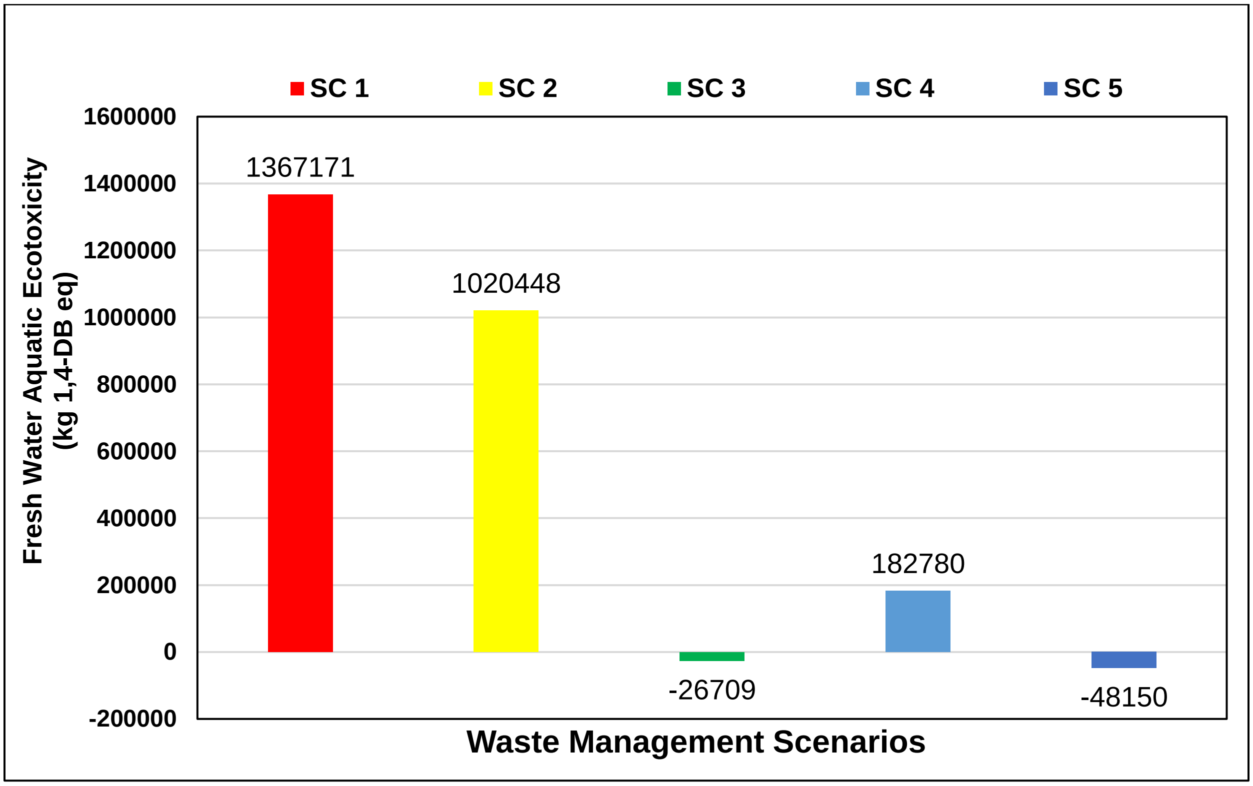


Figure 15: Scenario Comparison for Fresh Water Aquatic Ecotoxicity

Comparing the five scenarios examined, unsanitary landfill scenarios show a larger risk for freshwater ecotoxicity. Leachate is produced during the functioning of unsanitary landfills and contains a range of contaminants that can be discharged into surrounding bodies of water. These contaminants can harm aquatic habitats and creatures, which increases the toxicity of freshwater environments. The value of freshwater aquatic ecotoxicity for scenario 1 is 1,367,171 kg 1,4 DB eq. the least impact for the indicator was shown by incineration scenario with a value of -48,150 kg 1,4 DB eq. showing environmental savings.

As they frequently entail better regulated procedures that reduce the flow of pollutants into aquatic bodies, anaerobic digestion and incinerator scenarios, in contrast, show net environmental savings. When compared to landfill settings, these managed waste management techniques have a lower potential for freshwater ecotoxicity.

4.3.6. Scenario Comparison for Terrestrial Ecotoxicity

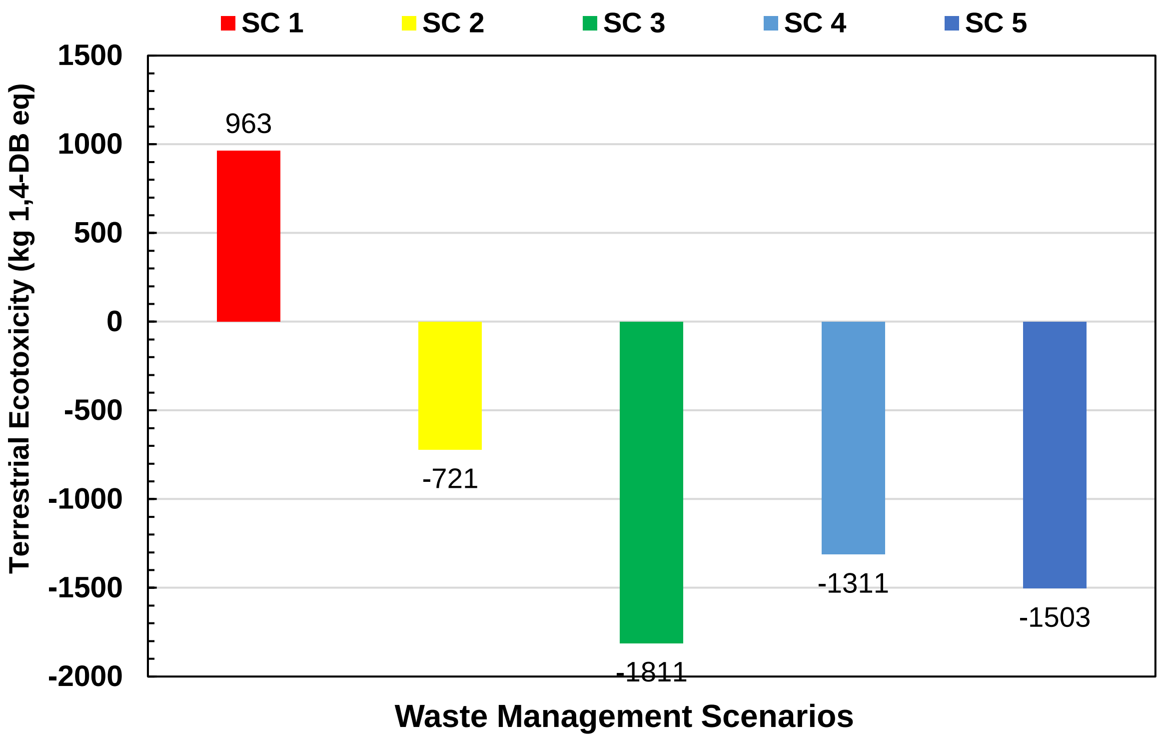


Figure 16: Scenario Comparison for Terrestrial Ecotoxicity

The discharge of pollutants and toxins into the soil through leachate is an aspect of the unsanitary landfill scenario. This pollution of the soil has an unfavorable impact on terrestrial organisms. Scenario 3 (Anaerobic Digestion) has the greatest environmental savings, in comparison. This is explained by the fact that anaerobic digestion, which involves the controlled breakdown of organic waste, limits the release of hazardous compounds into the environment. The highest environmental savings were shown by scenario 3 with a value of -1811 kg 1,4 DB eq. followed by S5, S4 and S2 respectively. The highest impact on terrestrial ecotoxicity was shown by S1 with a value of 963 kg 1,4 DB eq.

These results highlight how crucial it is to implement waste management strategies that prioritize regulated operations to reduce soil pollution and save terrestrial species. Anaerobic digestion may be used as a waste management alternative, reducing the possible negative effects on soil quality and terrestrial ecosystems and promoting more ecologically friendly and sustainable waste management practices.

4.3.7. Scenario Comparison for Acidification

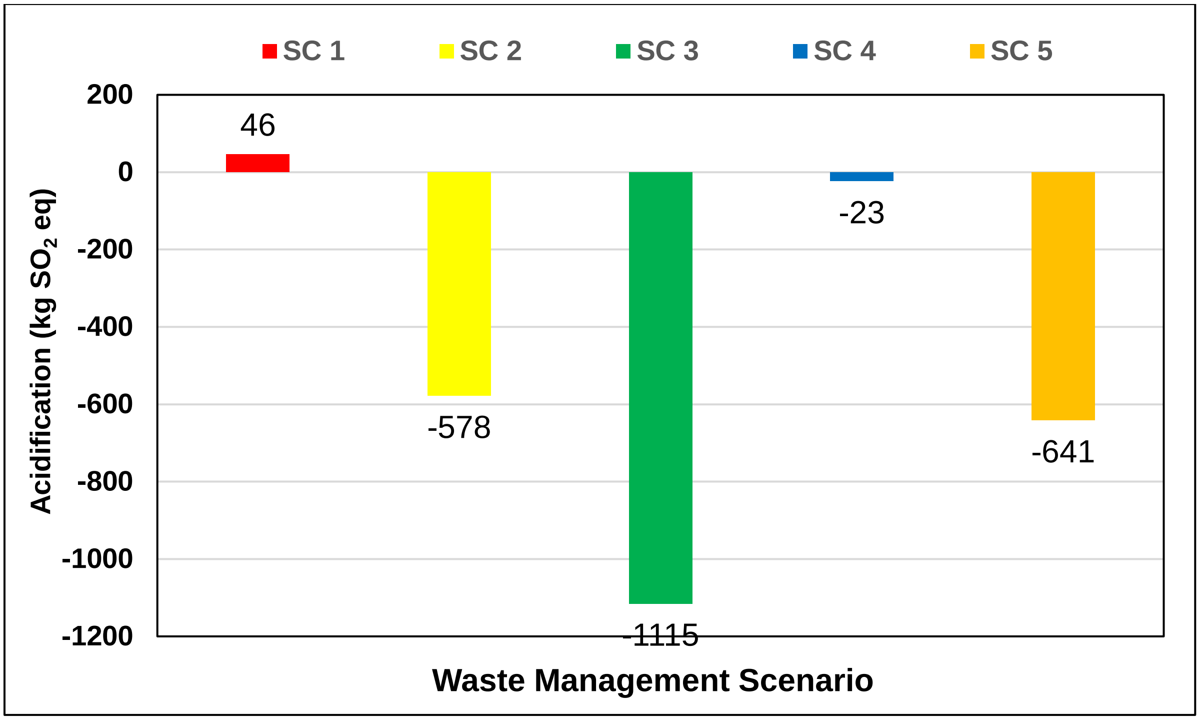


Figure 17: Scenario Comparison for Acidification

Compared to the other evaluated waste management scenarios, unsanitary landfill scenarios have the most potential for acidification and a beneficial impact on the environment. Anaerobic decomposition of organic waste produces a substantial amount of methane, which is a precursor to acid rain, as a result of the operation of unhygienic landfills. This increases the possibility for acidification in such settings. S3 showed least environmental impacts and highest environmental savings in terms of -1115 kg SO_2 eq. followed by S5, S2 and S4 with values of -641, -578 and -23 kg SO_2 eq. respectively.

On the other hand, scenarios including anaerobic digestion, sanitary landfills, composting, and incineration include steps to trap or minimize methane emissions, lowering their potential for acidification. These alternate methods of waste management put a lot of emphasis on managing organic waste well, which helps reduce the emission of methane and the possibility for further acidification. Additionally, energy recovery and the avoidance of emissions are responsible for the net environmental savings shown in these scenarios.

4.3.8. Scenario Comparison for Eutrophication

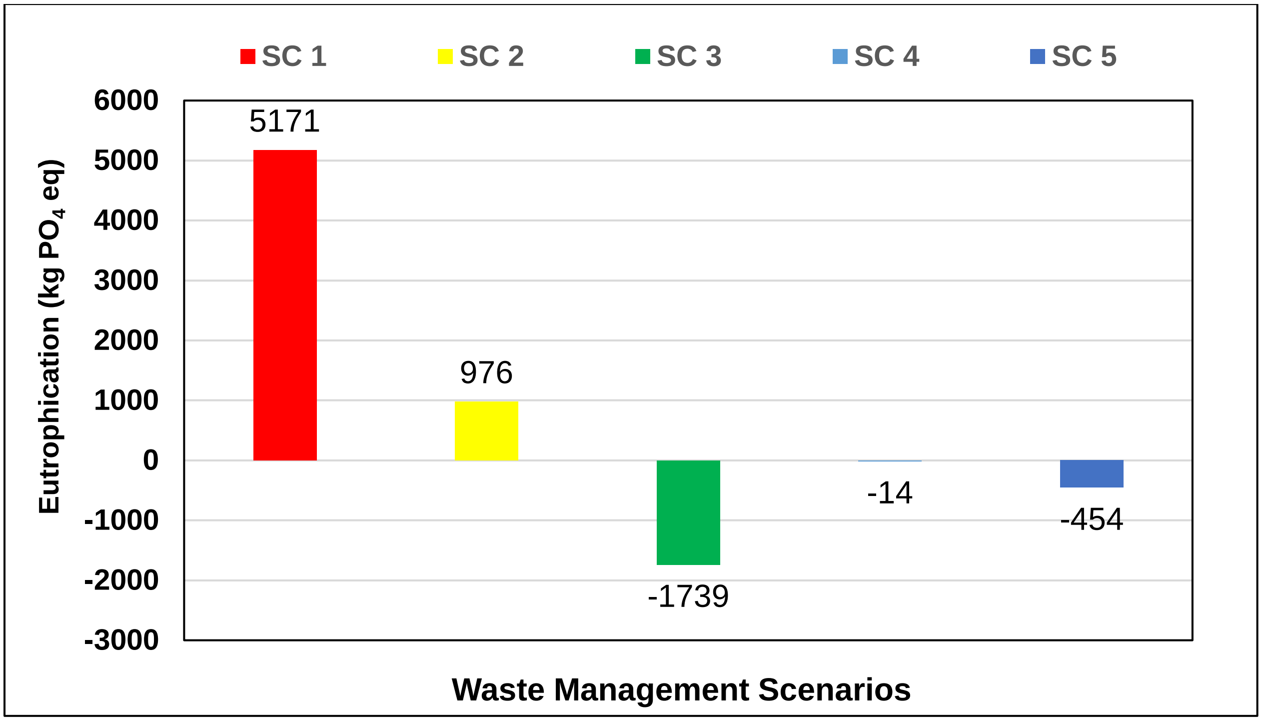


Figure 18: Scenario Comparison for Eutrophication

Eutrophication is largely caused by the discharge of leachate containing nutrients like nitrogen and phosphorus into neighboring ecosystems in both sanitary and unsanitary landfill settings. Eutrophication results from the overabundance of these nutrients, which cause algae blooms and oxygen depletion in aquatic bodies. On the other hand, scenarios including anaerobic digestion, composting, and incineration include the correct management and treatment of organic waste, minimizing the release of nutrients into the environment. The value of eutrophication potential was highest for S1 with a value of 5,171 kg PO_4 eq. followed by S2, S4, S5 and S3 respectively. Digestate and compost, which are produced by the anaerobic digestion and composting processes, respectively, can be used as controlled-release fertilizers that are rich in nutrients. Additionally, the cremation process catches and regulates nutrient emissions, which adds to the environmental benefits by reducing the likelihood of eutrophication.

The environmental burdens of unsanitary landfill scenario are greater in all impact categories. Scenarios using anaerobic digestion, composting, and incineration show environmental savings and better results in terms of these impacts. Thus, opting these treatment options will generate environmental benefits.

4.4. Sensitivity Analysis of Modelled Scenarios:

An important instrument for examining the reliability of findings and their susceptibility to uncertainty factors in life cycle assessments is sensitivity analysis (SA). In order to increase outcome interpretation, it emphasizes the most crucial set of model parameters. For this study the recycling efficiency of the study was used as a parameter for sensitivity analysis. In compliance with ISO 14042, a sensitivity analysis was performed using 3 different recycling rates. All scenarios involving recycling were at 50% efficiency for the study which were increased to 70% and 85% for sensitivity analysis.

If we exclude long term emissions Human Toxicity and Fresh Water Aquatic Eco toxicity both show environmental benefits at 70% and 85% recycling rates. Because less refuse enters the waste stream and requires an ultimate disposal, increasing recycling rates from 50% to 70% and 85% has a beneficial effect on freshwater aquatic Eco toxicity, global warming, and acidification. The sensitivity analysis on 3 scenarios was performed including Scenario 2, scenario 3 and scenario 5. The results of the sensitivity analysis are shown below. The positive impacts are visible since it's a MRF requiring energy to operate which engenders environmental burdens.

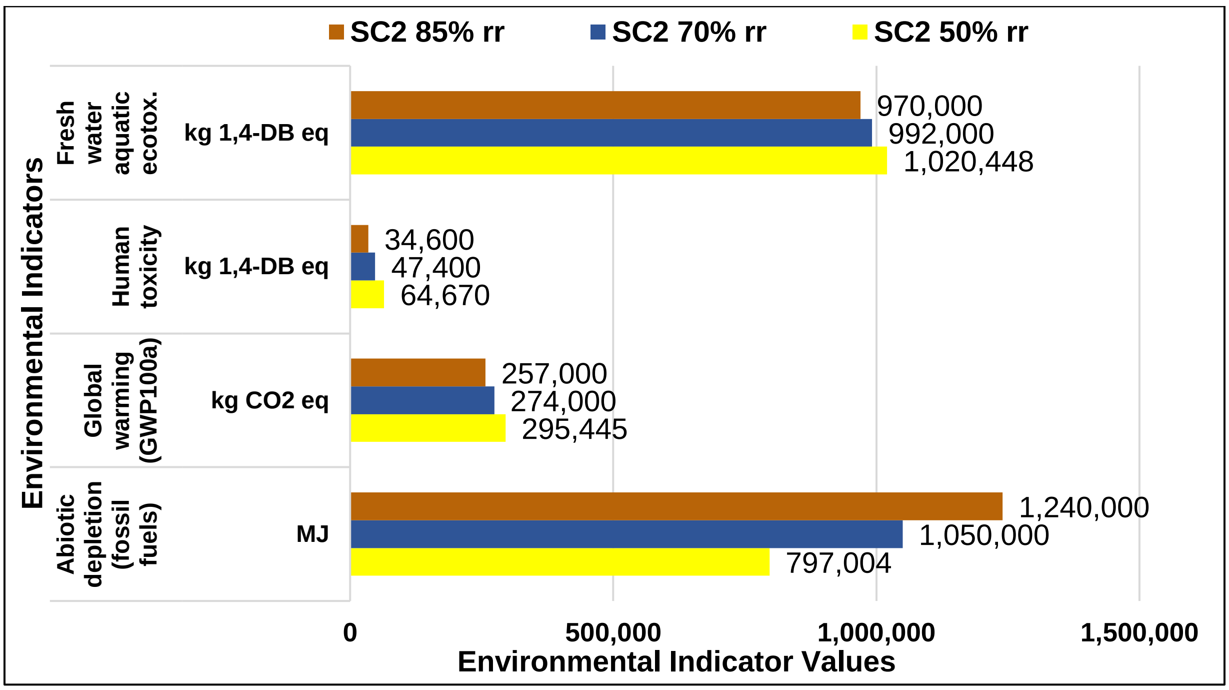


Figure 19: Sensitivity Analysis of Scenario 2 (Sanitary Landfill) at 50%, 70% & 85% Recycling Rate

The results show improvements in overall environmental indicators as the recycling rates are increased. The trend depicts that the effect of recycling rate fluctuates that validates the results of the study.

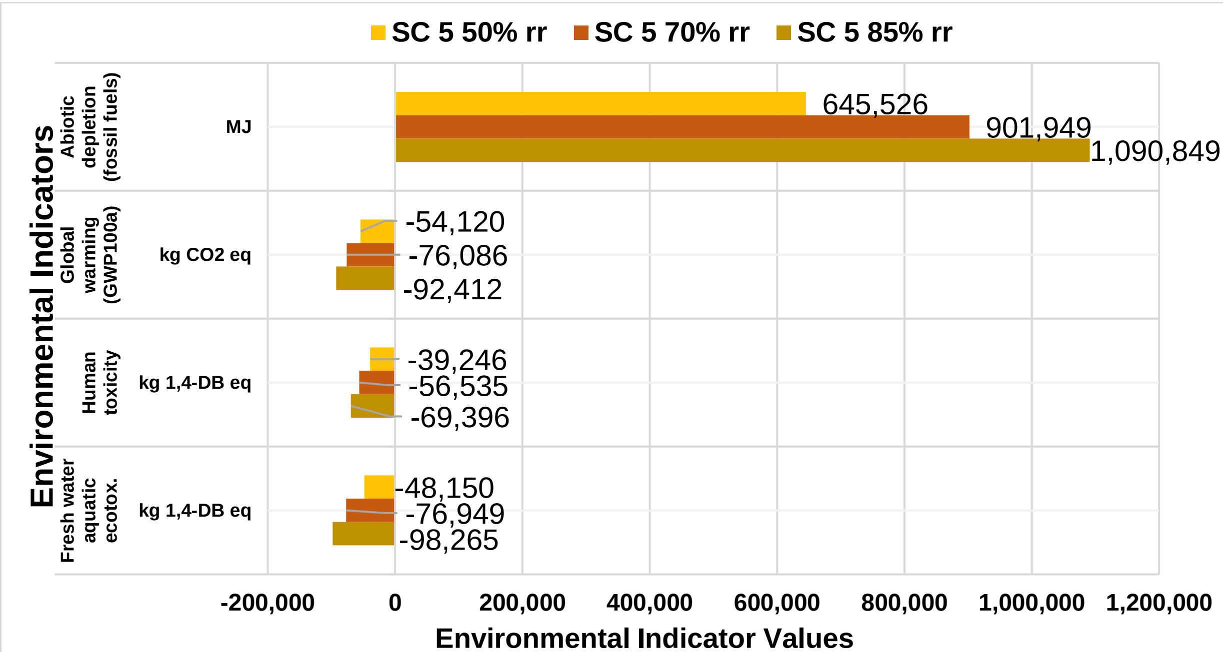


Figure 20: Sensitivity Analysis of Scenario 5 (Incineration) at 50%, 70% & 85% Recycling Rate

The environmental implications of Scenario 5 (Incineration), notably in terms of Fresh Water Ecotoxicity, Human Toxicity, and Global Warming Potential, showed changes and improvements. For GWP and up to 104% for FWE, increasing recycling rates from 50% to 85% led to greater environmental savings; a similar trend was seen for HT. However, due to extra loads from the Material Recovery Facility (MRF), the Abiotic Depletion indicator indicated a possible rise of up to 68%.

Similar to this study, a sensitivity analysis of Alternative 5 (MRF, composting, incineration, and landfilling) for the Turkish city of Eskisehir showed improved environmental benefits for all evaluated metrics when the recycling rate was raised from 40% to 100%. These findings demonstrate the value of waste management and recycling strategies for minimizing negative environmental effects and maximizing positive environmental outcomes. In particular with regard to fresh water ecotoxicity, human toxicity, and global warming potential increasing recycling rates can dramatically lessen environmental burdens.

5. CONCLUSION AND RECOMMENDATIONS

This chapter summarizes the study's main conclusions and derives actionable recommendations from them. It addresses the research goals and respond to the inquiry that was presented at the outset of the study. The important takeaways from the analysis are highlighted in the chapter, along with their implications for the larger study area or context.

5.1 Interpretation Stage of the Life Cycle Impact Assessment Results

The findings from the assessment are thoroughly analyzed and interpreted in the interpretation stage of the Life Cycle Impact Assessment (LCIA) outcomes. In order to do this, it is necessary to identify the major factors that have an influence on the environment and analyze the consequences of the findings in light of the study's goals. The interpretation step offers a greater comprehension of the environmental impacts of the evaluated life cycle and aids in informing the selection of sustainable practices and actions.

5.1.1 Conclusion of the Study

It has been determined, considering the findings of the LCA analysis, that the adoption of an integrated waste management system is crucial for the sustainable management of city waste. The current waste management system in Islamabad has significant environmental challenges including inadequate waste collection, limited recycling facilities and improper disposal practices.

Scenario 3 i-e, anaerobic digestion of the organic fraction along with recycling and final disposal to a sanitary landfill is the best in case of Islamabad considering the waste composition, moisture content and other factors in focus followed by Scenario 5 and Scenario 4. All biological treatment options for organic fraction of waste are highly reliable.

Municipal solid waste in Islamabad contains ingredients easy to recover and recycle, but municipal waste management suffers from the challenges of combined waste collection and storage as well as sustainable waste management strategies. Simultaneously, it lacks public and institutional awareness of waste recycling and its financial worth. Improvement in recycling rates can also aid in reducing the overall environmental burdens arising from the functioning of the recycling process

The limitation faced during this study included the absence of inventory data of Pakistan in the Ecoinvent database or any other source. This study is restricted to evaluating Islamabad's current waste management system solely from an environmental standpoint. The choice of a superior waste management scenario necessitates careful evaluation of a variety of factors because modern waste management is highly complex. Sustainable waste management systems must take social factors into consideration during the planning phase. Social considerations must be added to system analysis tools like LCA in order to better understand the processes of the future socio-technical waste system.

5.1.2 Recommendations of the Present Study

The recommendations devised after analysis and evaluation of the results of this study are as under:

- Sanitary landfills for the disposable fraction of the municipal solid waste should be introduced in Islamabad.
- Enhance waste collection infrastructure and promote recycling initiatives to divert recyclable materials from the waste stream.
- In future LCA studies, it would be prudent to categorize 30% of uncollected waste as openly dumped waste in case of Islamabad.
- Establish anaerobic digestion and composting facilities in Islamabad to process the organic fraction of waste, extracting energy in the form of biogas and producing nutrient-rich digestate for potential agricultural use.

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