ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF ORGANIC WASTE MANAGEMENT OPTIONS FOR A UNIVERSITY CAMPUS

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A thesis submitted to the National University of Sciences and Technology, Islamabad,

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Supervisor: Dr. Musharib Khan

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It is certified that the contents and form of the thesis entitled

"Environmental Life Cycle Assessment of Organic Waste Management Options for a University Campus"

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Dedication

This research is dedicated to the cherished memory of my late father, whose unwavering support and encouragement guided me throughout my academic journey. I am also deeply grateful to my mother for her enduring love, sacrifices, and belief in my aspirations. This work is a tribute to their profound influence and the values they instilled in me.

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Abstract

The study presents a comprehensive assessment of waste management practices at NUST, using a Bin-to-Cradle approach. The functional unit considered is the treatment of 1 metric ton of organic waste, encompassing resource recovery, highlighting the environmental implications of various scenarios. Sampling had been carried out in different sections of the campus, with waste audits completed both in the summer and winter. Five waste management scenarios were considered: open dumping, sanitary landfill, composting with landfill, anaerobic digestion with landfill and combination of composting, anaerobic digestion with landfill. SimaPro software and the ReCiPe 2016 approach were used to assess environmental liabilities and benefits. Results reveal that sanitary and open dumping are the least sustainable options due to adverse impacts like methane emissions and water pollution. Composting and anaerobic digestion emerge as more environmentally friendly alternatives, Anaerobic digestion with landfill (Scenario 3) has the lowest global warming potential while providing considerable benefits in terms of nutrient retention and renewable energy generation. The study emphasizes the importance of considering long-term emissions and specific organic waste management activities in assessing environmental performance. Anaerobic digestion is identified as the most advantageous option for managing organic waste, supported by evidence from previous research. These findings underscore the need for sustainable organic waste management practices to mitigate environmental impacts effectively.

Chapter 01: Introduction

Urbanization and population growth are the critical concerns of the century. In consequence, there is a substantial increase in solid waste generation leading to significant socioeconomic and environmental impacts (Ashra, Hameed, and Chaudhary 2016). This escalating issue poses challenges such as waste management and heightened pollution levels, impacting both human wellbeing and ecological sustainability (Akmal and Jamil 2021). By 2050, the world population is expected to exceed 10 billion, intensifying the global demand for organic waste resources and straining food supply systems (Sahoo et al. 2023). Pakistan is experiencing rapid population growth which generates 49.6 million tonnes of Municipal Solid Waste (MSW) annually. The maximum percentage of 50-60% comprises of organic waste (Development Bank 2021). The escalating issue of waste management and environmental degradation is often overlooked in case of educational institutions.

The substantial volume of waste generated in their daily operations consists primarily of organic waste (Adeniyi and Afon 2022). Modern universities with their diverse activities, encounter numerous environmental challenges that call for institutional accountability (Gallardo et al. 2016). Considering 244 educational institutions of Pakistan, the increasing waste generation, energy shortages, and waste disposal logistics underline the crucial need for enhanced waste management. (Korai, Mahar, and Uqaili 2016). Having a world of global warming, appropriate waste disposal is critical for sustainability and reducing human-caused environmental damage (Matthews and Themelis 2007). It is highly critical when considering that improper organic waste disposal can result in the release of methane, a potent greenhouse gas. When organic waste decomposes anaerobically in landfills, it emits around 60% methane and 40% CO2, aggravating climate change and rising global temperatures (Ramachandra et al. 2018).

Directing to reduce methane emissions and divert waste from open dumping and unsanitary landfills, local and state governments all around the world are rapidly implementing ambitious "zero waste" plans. The regulations acknowledge that unsanitary landfilling is the most GHG-intensive option, generating over 400 kg of methane per tonne of organic waste (Batool and Chuadhry 2009; Nordahl et al. 2020; Sánchez et al. 2015). In Pakistan alone, unsanitary landfills are estimated to produce 14.18 Gg (giga-grams) of methane annually (Zuberi and Ali 2015).

The European Union Commission developed the waste hierarchy to help developing countries reduce solid waste, realizing the adverse impacts of landfilling (Council 2020). Organic solid waste incineration with energy recovery often remains overlooked due to its high moisture content and non-combustible components (Pham et al. 2015). Sanitary landfilling, while seen as a last choice, remains crucial when recycling or recovery isn't achievable due to rigorous environmental regulations. Composting reduces landfill waste, methane emissions, and improves soil quality, whereas anaerobic digestion turns organic waste into biogas and nutrient-rich byproducts, resulting in less waste and reduced greenhouse gas emissions. In addressing waste management challenges in Pakistani institutions, a holistic approach is crucial. Life Cycle Assessment (LCA) offers a comprehensive evaluation of the environmental impact at each waste management stage (Pham et al. 2015; Ramachandra et al. 2018). This empowers universities to identify environmental concerns and take (Guven, Wang, and Eriksson 2019; Ramachandra 2002). In this study, a unique challenge of organic waste management is uncovered. While prior studies have explored the impact of food waste in cities, there's a significant gap when it comes to understanding the environmental effects of organic solid waste in Pakistani institutions (Banar, Cokaygil, and Ozkan 2009; Buratti et al. 2015; Mandpe et al. 2022). To address this gap, this study diligently gathered data on waste collection and transportation which is a frequently overlooked aspect in prior research (Jaglan et al. 2022). Given the limited number of prior LCA studies for organic solid waste management in this region, this research contributes valuable insights benefiting Pakistani universities and offering guidance to institutions in developing countries.

In this study, the environmental impact of university is comprehensively assessed for solid waste in Islamabad, Pakistan, using the LCA approach. The waste management strategies such as landfilling, composting, and anaerobic digestion have been compared to identify the most effective and environmentally responsible approach. This research provides practical insights for decision makers, policymakers, and stakeholders, aiming to minimize the environmental footprint of university waste management and foster sustainability.

1.1 Problem Statement

There is a huge number of educational institutions in the country which generate considerable solid waste which is often either improperly disposed of or inadequately utilized for beneficial purpose. To identify solid waste management option(s) having least environmental impact, availability of knowledge of the following important aspects is crucial, which is currently missing in the literature:

a) Generation rate and characteristics of solid waste
b) Environmental life cycle assessment of waste management options

1.2 Objectives

The objective of this study is to conduct a comprehensive waste accounting and characterization analysis for the university campus, which will provide a detailed understanding of the types and quantities of waste generated. This analysis will be complemented by the utilization of Life Cycle Assessment (LCA) as a comparative tool to evaluate the environmental impacts of various solid waste management methods currently employed on the campus. Through this process, the study aims to identify the most environmentally sustainable waste management option that aligns with the principles of a circular economy, thereby promoting resource efficiency, reducing environmental footprint, and enhancing the overall sustainability of the campus waste management system.

Chapter 02: Literature Review

This chapter offers an analysis of the literature that provides an in-depth investigation of existing scholarly works and research findings related to the topic under assessment. It establishes a fundamental understanding of the issue, identifies gaps in current knowledge, and lays the platform for the research done in this study.

2.1 Municipal Solid Waste

Municipal solid waste is a diverse variety of solid discards produced every day by both urban and rural populations, appearing as garbage, refuse, and trash. Municipal solid waste, which is generated by households, offices, small-scale organizations, and commercial enterprises within a municipality, varies significantly in composition and categorization throughout municipalities worldwide. It includes both biodegradable and non-biodegradable fractions formed from organic and inorganic sources. Kitchen garbage, yard waste, paper and cardboard, plastic and rubber, metal, glass, electronic waste, inert materials, and miscellaneous refuse are all common constituents of municipal solid waste. These waste types are combined in the organic part of municipal solid garbage. Among all the constituents of municipal solid waste, the miscellaneous garbage component is the most diverse. Textiles, fabrics, biological wastes (such as sharps and glasses), personal hygiene products, healthcare supplies, pharmaceuticals, cosmetics, pet litter, leather, rubber, and polymeric residues are just a few of the many products that fall under this broad category (Nanda and Berruti 2021).

An overview of municipal solid wastes is provided by the items on the following list. Recognizing that municipal solid waste composition, classification, and categorization vary from nation to nation and city to city is imperative. This variation depends on regional policies and the classification given to solid waste in each locality.

Approximately one-third of the projected 2 billion tons of municipal solid trash generated globally each year is not collected by municipalities. Globally, each person produces 0.74 kg of waste every day on average (Anon n.d.-c).According to World Bank projections , the amount of municipal solid trash produced is predicted to increase to 3.4 billion tonnes by 2050. Approximately 70% of the municipal solid waste that municipalities collect ends up in landfills or dumpsites, 19% is recycled, and 11% is used for energy recovery. With 8.01 billion people on the planet as of 2023

(Bureau 2024), 3.5 billion of them alarmingly lack access to basic waste management services (Kaza, Yao et al. 2018). Forecasts indicate that by 2050, this figure may rise to 5.6 billion, indicating a growing difficulty in delivering basic waste management services.

The management of municipal solid waste (MSW) in Pakistan faces a myriad of challenges, reflecting a situation common to many developing countries. The degradation of waste management in Pakistan is attributed to various factors, including political negligence, insufficient financial resources, technological limitations, public awareness and behavioral issues, and administrative shortcomings. The prevalence of open disposal as the primary technique for MSW management underscores the absence of sanitary landfills across the country. Consequently, major cities and small towns in Pakistan bear witness to a visible manifestation of neglect and mismanagement in MSW handling, significantly impacting both environmental and social life quality. Despite being classified as a lower-middle-income country, Pakistan grapples with severe environmental and public health problems due to the lack of a sustainable waste management policy and infrastructure. This void has contributed to the escalation of public concerns regarding uncontrolled and open waste disposal, exemplified by the sight of accumulating solid waste in 11 major cities like Karachi, Lahore, and Islamabad (Mahar et al. 2007).

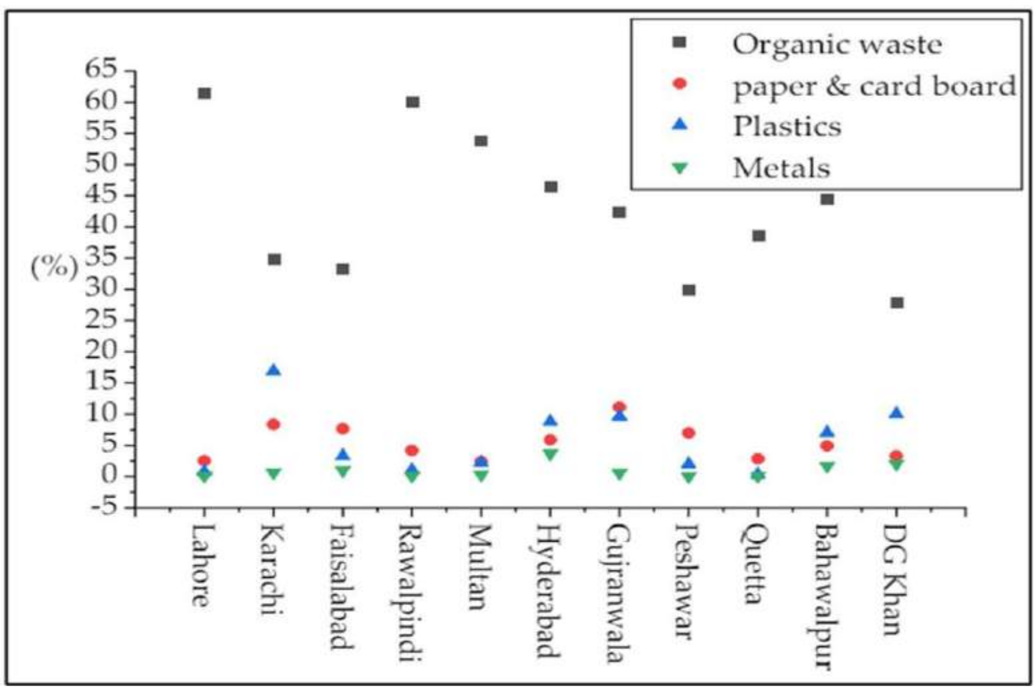

Figure 2.1 Percentage of waste composition of 11 cities *(Mahar et al. 2007)*

The existing legal framework pertaining to solid waste management in Pakistan is deemed inadequate and outdated, as indicated by the Pakistan Environmental Protection Agency (PEPA) guidelines from 1997 (Sohoo et al. 2022). While guidelines for hospital waste management have been in existence since 1998, offering comprehensive information on safe hospital waste practices, the non-implementation of these guidelines has led to a haphazard disposal of medical waste. Hospital waste is often mingled with municipal waste in roadside collection bins, and some waste is buried without proper measures. The urgent need for legislation in solid waste management is evident, encompassing regulations that clearly define the responsibilities of citizens, enterprises, and the government. Stringent penalties for violations should apply to citizens, businessmen, factory owners, and the government alike (Henry, Yongsheng, and Jun 2006).

At the administrative level, the Planning & Development Division at the federal and provincial levels, along with the Ministry of Environment and the Pakistan Environmental Protection Agency (PEPA), are tasked with the formulation of policies and implementation of environmental protection laws. However, the practical implementation of these regulations faces significant hurdles at the local level. Town and Tehsil Municipal Administrations (TMAs), responsible for solid waste collection, transportation, and disposal, encounter challenges stemming from a lack of funds, rules, standards, expertise, equipment, and vehicles. These limitations render them incapable of effectively managing the continuously increasing volumes of municipal (Buratti et al. 2015).

Considering these challenges, there is an urgent need for a comprehensive and updated solid waste management policy that addresses the shortcomings in legislation, enforcement, and infrastructure. Effective waste management strategies should encompass the involvement of citizens, businesses, and government entities, with a focus on sustainable practices, efficient resource allocation, and stringent enforcement of regulations. Additionally, investments in technology and infrastructure are crucial to modernize waste management practices and mitigate the adverse environmental and public health impacts associated with mismanaged MSW in Pakistan.

2.1.2 Organic Fraction of Municipal Solid Waste

There are regional and national variations in the definition of the organic fraction of municipal solid waste (OFMSW) across the globe. In the United States of America, OFMSW is recognized as a combination of food, garden waste, and paper. On the other hand, in the European Union, it is identified as a mixture derived from parks, gardens, and kitchens (Campuzano and González-Martínez 2016).

The term Organic fraction municipal solid waste (OFMSW) refers to biodegradable waste that comes from a variety of sources, such as parks, gardens, homes, restaurants, retail stores, catering businesses, and the food industry. This waste is usually collected by municipal authorities. Typically, it is made up of a combination of food waste, cardboard, newspapers, wood, and different types of paper. However, there are significant national variations in the categorization and attributes of OFMSW, which are impacted by a multitude of factors. Various food preparation residuals, including fruit and vegetable peelings, bread, meat and fish, snacks and sweets, dairy, tea bags, coffee granules, cereals, and other leftover foods, have been classified into 16 fractions of OFMSW in previous research reports. The simultaneous presence of both biodegradable and non-biodegradable waste, including items like eggshells, bio bags, and bones, can adversely affect anaerobic digestion, with non-biodegradable wastes considered as physical impurities (Zamri et al. 2021).

The characteristics and composition of OFMSW are heavily influenced by the waste management system adopted. Different collection techniques are used in Europe, such as sorting at the source (SS-OFMSW), separate and collect (SC-OFMSW), and mechanical separation (MS-OFMSW). When combined with large grain-sized collected waste, the MS-OFMSW method works well. The main goals of this separation are to minimize waste volume, separate organic waste with a high calorific value from inorganic waste and homogenize both for later energy recovery (Zamri et al. 2021).

2.1.3 Waste Generation in Pakistan

Pakistan generates about 0.6 kg of waste per person per day on average. The rates of production of waste are different for high, middle, and low-income groups; they are 0.890, 0.612, and 0.346 kg per person per day, respectively. The study revealed a noteworthy seasonal effect on waste generation, with lower amounts during the summer and monsoon seasons and higher amounts in the spring and winter. The consistent observation that food waste accounts for the largest portion of waste across all income groups and seasons was an interesting finding. This pattern, in which food waste becomes the largest portion, is not limited to Islamabad; it is also apparent in other major Pakistani cities, like Lahore, Karachi and is consistent with trends seen in other developing nations. It is important to note that this trend varies in developed nations due to the ubiquity of packaged and processed foods, which modifies the makeup of waste. A significant potential for composting or bio-gasification techniques is indicated by the higher percentage of food waste in Islamabad's waste stream. This indicates opportunities for sustainable waste management practices in the area (Masood, Barlow, and Wilson 2014; Tyagi et al. 2018; Yhdego 1988).

Urbanization, population growth, changing lifestyles, and economic development all play major roles in Pakistan's increasing production of MSW (municipal solid waste). The increase in solid waste presents significant obstacles to the effectiveness of waste management procedures, which include disposal, storage, and transportation. Regional, climatic, and socioeconomic factors all have a substantial impact on the amount and makeup of solid waste worldwide. Just 60% of waste is collected in many Pakistani cities, and an astounding 90% of collected waste ends up in open dumping sites. More than 75 percent of waste must be collected to keep cities relatively clean. One example is the estimated 0.84 kg/capita/day MSW generation rate in Data Ganj Bakhash Town, Lahore City, Pakistan. This results in a daily total of 1369.8 tons of waste, of which 67.02% is organic waste (Ilyas et al. 2017).

However, effective waste management in Pakistan faces significant hurdles, including the lack of reliable data, inadequate institutional arrangements, non-compliance with laws, limited resources in terms of finance and equipment, and a shortage of trained manpower. Urbanization brought on by rural-to-urban migration has caused Pakistani cities' population rates to rise noticeably over the past ten years, from 3.7% to 7.4%. The difficulties in managing the nation's growing MSW volume are exacerbated by this demographic shift (Tyagi et al. 2018).

2.1.4 Effects of Mishandling of Organic Waste

Global urbanization has experienced a global surge, with big cities becoming the economic engines of their respective nations. But there is a big drawback to this urban growth: a large amount of solid waste is being generated. The rapid increase in population aggravates an already unstable supply and demand chain, leading to higher prices for everyday goods, difficulties obtaining clean drinking water, and pressure on waste disposal infrastructure. The potential risks that improper waste disposal poses to human health and the environment highlight the importance of effective waste management (Masood et al. 2014).

Ineffective waste management techniques have negative effects that go beyond the waste itself. Inadequate methods of treatment, like releasing disagreeable odors and encouraging the growth of rodents and insects, can exacerbate the damage. The consequences of illegal dumping or mishandling municipal solid waste (MSW) have a wide range of negative effects on the environment. These include the spread of disease vectors, unpleasant odors resulting from the breakdown of organic fractions, air pollution caused by open biomass burning, leaching of toxic compounds affecting groundwater quality, the effects of climate change and atmospheric photochemical reactions, the degradation of existing landscapes, and contamination of soil and surface water bodies (Babu, Prieto Veramendi, and Rene 2021).

Innovative hybrid treatment technologies must be quickly adopted to lessen these negative effects. These technologies seek to enable resource recovery from waste in addition to addressing the problems caused by MSW. A sustainable bioeconomy must be achieved through the use of such technologies, especially in developing nations where the demands of waste management and urbanization are more acute (Babu et al. 2021).

2.2 Advantages of Organic Waste Management

Municipal solid waste (MSW) is a growing issue that is impeding society's ability to develop harmoniously. Classifying municipal solid trash is now considered by China to be one of the key tactics for building a national ecological civilization. The research presented in Matthews and Themelis 2007's paper shows that the socioeconomic advantages of managing municipal solid waste (MSW) are greatly increased by the application of waste classification. The socioeconomic benefits may change from negative to positive values as the rate of waste separation rises. Interestingly, the generated socioeconomic benefits may amount to as much as 0.36 % of GDP when the separation rate reaches 100%. When comparing scenarios with no waste separation to those with a 100% separation rate, the results show that the annual reduction of greenhouse gas emissions (CO_2-equivalent) from 2006 to 2017 could have ranged from 1.03 to 1.46 million tons in terms of environmental impact. Furthermore, the study shows that the range of land resources saved could vary from 502.92 to 2915.59 square meters for every 1% increase in the separation rate.

The social, resource, and environmental benefits of waste classification are highlighted by this research, which gives sustainable urban development new life. It is crucial to emphasize that more Anaerobic Digestion (AD) plants need to be installed in order to stop classified food waste from being disposed of in landfills or burned. The System Dynamics (SD) model used in this work highlights the crucial role of waste classification and offers insightful information for researchers, policymakers, and strategic planners. Regulations should be implemented concurrently to encourage recycling, waste separation, and residents' active involvement in waste separation practices (Wang and You 2021).

2.3 Life Cycle Assessment

The concept of Life Cycle Assessment (LCA) emerged in the 1960s, initially with a focus on energy and resource inventory. Over time, efforts were made to standardize LCA, leading to the establishment of international standards in 1993, with the final version published in 2006 as ISO 14040. LCA is a unique environmental assessment tool that avoids biased ratings resulting from burden shifting, making it a reliable approach to evaluating environmental impacts considering factors like costs, social implications, and feasibility. It links impacts to system function for comparison (Bilgili and Çetinkaya 2023)(Klöpffer 1997). Life Cycle Assessment (LCA) is a decision-making tool that optimizes technological solutions within limited resources. It evaluates the entire life cycle of a product or service, prevents burden shifting, and links environmental performance to functionality. LCA is known as "eco-balance" in some languages, emphasizing the quantified inventory of emissions and resources(Jolliet et al. 2015). SETAC (Society of Environmental Toxicology and Chemistry) has defined LCA as "an objective process to assess the environmental impacts associated with a product, process, or activity, by quantifying energy and material use, waste releases, and identifying opportunities for environmental improvements". This definition aligns with the core principles of LCA, which involve identifying, quantifying, and evaluating the environmental burdens associated with a system, and seeking opportunities for improvement throughout its life cycle (Barton, Dalley, and Patel 1996).

2.3.1 LCA over Assessment Methods for Sustainability

The Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), Sustainability Assessment (SA), and Multi-Criteria Decision Analysis (MCDA) are different methods and tools used for evaluating the environmental and social impacts of decisions related to development projects, policies, and strategies (Jeswani et al. 2010).

2.3.1.1 Environmental Impact Assessment (EIA)

EIA can include several different methods and tools for analysis, depending on the technical/environmental content of the decision at hand. EIA is generally used to ensure environmental and social impacts are considered explicitly both during the design of a new development and in the project authorization decision. It is used as an aid to public decision-making on larger projects and is a mandatory requirement for certain development projects in many countries. Unlike EIA, which focuses mainly on local environmental impacts and qualitative assessments, LCA is a comprehensive and systematic method that considers the entire life cycle of a product or system, including its environmental, social, and economic impacts. LCA is a scientifically rigorous approach that provides quantitative and objective data, which can help in making informed decisions based on robust data and analysis. LCA also has standardized methodologies and guidelines, such as ISO 14040 and ISO 14044, which ensure consistency and comparability of results (Udo de Haes 1993).

2.3.1.2 Strategic Environmental Assessment (SEA)

SEA is like EIA but tends to operate at a 'higher' level of decision-making (i.e., for strategies and policies). Since SEA is conducted at an early stage, it is normally performed in conditions involving less information and high uncertainties. SEA application in Europe is mostly found during policy development, leading to policy selection (Ness et al. 2007). However, the adoption of the EU SEA Directive is now forcing way for enhanced SEA implementation throughout the EU. While LCA can be a valuable tool within the SEA framework as it provides a systematic approach to assess the environmental, social, and economic impacts of different policy options. LCA can provide quantitative data and analysis, which can help in comparing different policy options objectively. LCA also has established methodologies and guidelines that ensure consistency and comparability of results, making it a robust and transparent method for evaluating the sustainability of policy options.

2.3.1.3 Sustainability Assessment (SA)

Sustainability Assessment is an umbrella term that includes a range of methods and tools that may be known as 'Sustainability Appraisal', 'Sustainability Impact Assessment', 'Integrated Sustainability Assessment', or 'Integrated Assessment', amongst others. It is being applied to an ever-increasing range of decisions across the world, from policies to strategic plans to projects to trade agreements, at different levels from micro to macro and with different timing (ex-ante, during, ex post) to identify synergies and trade-offs among the different sustainability dimensions. While LCA can provide a robust and comprehensive assessment of the environmental, social, and economic impacts of different options, making it a valuable tool for sustainability assessments. LCA uses standardized methodologies and guidelines, which ensure consistency and comparability of results. LCA also provides quantitative data and analysis, which can help in making informed decisions based on objective data. Additionally, LCA can be integrated into other sustainability assessment methods, such as combining LCA with indicators of sustainable development, to provide a more comprehensive and holistic assessment of sustainability.

2.3.1.4 Multi-Criteria Decision Analysis (MCDA)

MCDA methods support the comparison of different options based on a set of decision criteria. Consideration of multiple criteria is particularly applicable to cases where a single-criterion approach (such as CBA) falls short, especially where significant environmental and social impacts cannot be assigned monetary values. Furthermore, MCDA tends to be more transparent than other methods such as CBA since objectives and criteria are usually clearly stated, rather than assumed. Whereas LCA can provide a comprehensive and systematic approach to assess multiple criteria, including environmental, social, and economic impacts. LCA uses quantitative data and analysis, which can help in objectively comparing different options based on multiple criteria. LCA also has established methodologies and guidelines that ensure consistency and comparison.

2.4 Goal and Scope

The first phase of a life cycle assessment (LCA) is crucial, as it involves defining the goal and system boundaries, which greatly influences the LCA results. As per ISO 14044 (section 4.2.2), the goal of an LCA should be clearly stated and include information such as the intended application, reasons for conducting the study, intended audience (i.e., who the results will be communicated to), and whether the results will be used in comparative assertions intended for public disclosure. It is essential to unambiguously define these items to ensure the clarity and accuracy of the LCA, as they form the foundation upon which the entire assessment is built (Klöpffer 1997).

2.4.1 System Boundary

According to ISO 14044, the system boundary is a set of criteria that define which unit processes are considered part of a product system. It encompasses the entire life cycle of a product, from waste generation to waste treatment, and includes the quantitative analysis of all inflows and outflows such as electricity, biogas, manure, leachate, recycled products, and emissions (Mandpe et al. 2022). The system boundaries determine which specific modules are included and excluded when modeling the system, aiming to encompass all required processes, from cradle to grave, to fulfill the product's function. However, achieving a complete life cycle assessment (LCA) can be challenging due to the need to cover and model all global production processes that occur throughout the production, use, and disposal chain.

2.4.2 Type of Waste

In the first audit conducted at the University, the waste generated on campus was classified into two primary categories: recyclable and non-recyclable waste. Recyclable waste was further divided into five sub-categories, while non-recyclable waste was divided into 11 sub-categories. A comprehensive description of each sub-category was provided to ensure accurate categorization of waste. This classification system can serve as a valuable tool for waste management and sustainability initiatives at the University. Following table 2.1 shows the description of each Sub-category.

Table 1.1 Description of general waste category (Demirbas 2011).

Waste Category	Description
Kitchen waste	Food, bread, vegetable, fruits, rice, etc.
Paper (recyclable)	All office paper, Newspaper, paperboard, tissue boxes, heavyweight folders, books, registers, food packing, empty coffee cups, etc.
Paper (non-recyclable)	Napkins, Tissue paper, paper towels, wax paper, wrapping paper, Milk/ Juice tetra pack
Textile	Fabric, Fabric bags, Cotton, Wool
Yard waste	Plants, grass, wooden pieces, dry/wet leave, Mud, etc.
Plastic (recyclable)	All plastic types: PET, food and beverage containers, Plastic cup/glass, milk jugs, clean grocery bottles, soap bottles, soda bottles, laundry detergent containers, etc.
Plastic (non-recyclable)	Plastic Baggies, Styrofoam Containers, Polythene
Leather and Rubber	Shoes, Bag, belt, Nylon Etc.
Metal (non-recyclable)	Paint cans, cardboard & metal mixed container
Metal (recyclable)	Metal and tin beverage containers, metal food containers, aluminum foil and containers, cutlery, tins, metal wires, metallic spare parts, etc.
Bottle & glass (non-re)	Broken window glass, mirror glass, crystal, etc.
Bottle & glass (recyclable)	Colored/ transparent glass bottles and jar.
Ceramic & stones	Stone, Ceramic, broken bricks
Domestic hazardous Waste	Safety Eraser, Medicine, and acid bottles, etc.
Sanitary	Diaper, Pads, etc.
Miscellaneous	Hairs, bones, waste particles difficult to identify, etc.

2.4.4 Function Units

As per ISO 14044 (2006), the functional unit (FU) is a quantified measure of the performance of a product system used as a reference unit. It describes the function of a system in terms of the service it provides and serves as the basis for calculating inventory flows and impacts in life cycle assessment (LCA). For example, in solid waste management (SWM) studies, a common FU could be the treatment of one tonne of waste, which allows for meaningful comparison among different waste treatment methods. Mass-related FUs are commonly used in SWM studies as they are based on waste weighing practices from site visits and government reports.(Mulya et al. 2022) Ensuring that all systems or scenarios being compared have the same FU is crucial for establishing the environmental inventory. Key parameters often measure environmental performance as ratios of material per function, while the FU itself is additive and not a ratio (i.e., impacts double when the FU doubles). This approach helps ensure consistency and accuracy in LCA comparisons.

2.4.5 Waste Management Facilities

Waste management facilities are specialized sites that are responsible for handling and processing various types of waste, such as domestic, commercial, industrial, and hazardous waste. These facilities utilize a range of technologies, including incineration, gasification, anaerobic digestion, and landfilling, to convert waste into valuable products or energy. The selection of technology employed is dependent on the type and quality of waste, as well as local conditions. The primary objective of waste management facilities is to minimize the amount of waste that ends up in landfills, reduce pollution, and generate useful products and energy from waste. Effective waste management facilities should be cost-effective, require minimal land area, and cause minimal air and land pollution. They should also produce more power with less waste and maximize volume reduction. Modern waste management facilities incorporate advanced techniques to categorize and segregate different types of waste and use various treatment processes to manage and convert waste into valuable products. Ultimately, the development of waste management facilities is critical in ensuring sustainable waste management practices and minimizing environmental pollution (Demirbas 2011).

There are several types of waste management facilities designed to handle specific types of waste and employ different technologies to manage and dispose of waste effectively.

2.4.5.1 Sanitary Landfills

A sanitary landfill is not a natural environmental condition, but rather a container designed to prevent degradation and protect the environment from harmful contamination. Organic waste, even paper and grass clippings, degrade slowly in landfills due to the lack of air and water. Landfill leachates contain numerous compounds that can pose a threat to health and the environment if released. Effective management of municipal solid waste (MSW) has become a significant social and environmental concern. When not properly constructed, landfilling MSW can result in soil, surface water, and groundwater contamination. Leachate composition and flow rates vary from site to site and seasonally. Proximity or exposure to landfill sites has been associated with health risks such as birth defects and cancers. However, evidence linking waste landfills and incinerators to health endpoints is inadequate or insufficient. In Delhi city, 78.38% of the total MSW generated is landfilled, leading to emissions of methane, nitrous oxide, carbon dioxide, and leachate generation (Mandpe et al. 2022).

2.4.5.2 Composting

Composting is a sustainable process that involves the biological breakdown of organic matter under controlled aerobic conditions, resulting in the formation of a stable and nutrient-rich humus-like product. This process is essential for reducing the amount of organic waste that ends up in landfills and contributes to greenhouse gas emissions.

There are two main types of composting systems: turned and forced aeration systems. Turned systems involve piling the feedstocks in elongated heaps and turning them with decreasing frequency to maintain oxygen and moisture levels. Forced aeration systems are more complex, with computer-controlled aeration regimes that offer greater control over the process conditions. An optimized forced-aeration SW (solid waste) composting system typically consists of three main stages: the sanitization stage, the secondary biodegradation phase, and the tertiary phase for MSW compost maturation. In many countries, enclosed in-vessel systems are required for composting wastes containing food and animal by-products.

Inoculating SW with specific microorganisms can accelerate the composting process. Although open-air windrow systems are still commonly used for household and green waste composting, there is a trend towards in-vessel plants due to their increased efficiency and reduced environmental impact (Farrell and Jones 2009).

2.4.5.3 Anaerobic Digestion

Anaerobic digestion is a process that transforms organic waste into biogas and other energy-rich compounds through the activity of diverse microbial populations in the absence of oxygen. It is a useful technology for treating a wide range of organic materials, including municipal, agricultural, and industrial wastes, and plant residues. However, the rate of biodegradation of solid organic waste can be hindered by the complex structure of lignocellulose materials. Pre-treatments such as physical, chemical, and enzymatic methods are required to increase substrate solubility and accelerate the biodegradation rate of solid organic waste. The process of anaerobic digestion occurs in four basic steps:

- **a.** Hydrolysis, which breaks down complex organic matter into soluble compounds.
- **b.** Acidogenesis, which converts the soluble compounds into organic acids.
- **c.** Acetogenesis, which produces acetate and other compounds; and
- **d.** Methanogenesis, which produces biogas, mostly methane and carbon dioxide, as the end product (Khalid et al. 2011).

2.4.5.4 Incineration

Incineration is a waste disposal method that involves the combustion of waste material at high temperatures, often described as "thermal treatment." It is a widely used method to dispose of solid, liquid, and gaseous waste, and it is recognized as a practical way of disposing of hazardous waste materials such as biological medical waste. Incineration is carried out on both small and large scales by individuals and industry, with the goal of treating waste material while recovering heat energy from the combustion process. However, incineration remains a controversial method of waste disposal due to issues such as emission of gaseous pollutants and generation of solid residues, including bottom ash and air pollution control residues. Incineration residues not only have a high content of inorganic compounds but also abundant carbon compounds deriving from incomplete combustion, unburned organic matter, and carbon compounds formed during incineration. Therefore, it is essential to carefully monitor and manage incineration residues to minimize environmental impacts and potential health hazards (Demirbas 2011).

2.4.5.5 Waste to Energy Facilities:

Waste to energy (WTE) facilities are an essential component of waste management systems, which are designed to convert various types of waste, including municipal solid waste (MSW), industrial waste, and hazardous waste, into electricity, heat, or fuel. These facilities employ different technologies to process waste, such as combustion, gasification, and pyrolysis. Combustion involves burning the waste material at high temperatures, while gasification involves heating the waste in the presence of a limited amount of oxygen to produce a gas that can be burned for energy. Pyrolysis is the process of heating the waste in the absence of oxygen, which results in the production of gas, liquid, and solid by-products. These processes generate heat, which is used to produce steam, and the steam drives a turbine to generate electricity.

WTE facilities offer several benefits, including reducing the amount of waste that ends up in landfills, reducing greenhouse gas emissions, and providing a source of renewable energy. However, there are also concerns about emissions from these facilities, including air pollution and toxic ash residue. The implementation of WTE facilities requires careful planning, regulation, and monitoring to ensure their safe and efficient operation. In addition, the selection of the appropriate technology should be based on various factors such as the type and quantity of waste, the energy demand, and the environmental impact. Overall, WTE facilities play an important role in the management of waste and in the transition to a more sustainable energy future (Tabasová et al. 2012).

2.4.6 Life Cycle Inventory

Life Cycle Inventory (LCI) is a second step in Life Cycle Assessment (LCA) used to evaluate the environmental impact of a product, process, or service throughout its life cycle. It involves gathering and analyzing data on all the material and energy flows required to produce the product or service, as well as the associated emissions to air, water, and land. The inventory is organized into unit processes, representing distinct stages in the life cycle, from raw material extraction to end-of-life disposal. LCI provides the foundation for subsequent impact assessment and interpretation stages and enables businesses and policymakers to make informed decisions about environmental impact and identify opportunities for improvement in product design, manufacturing, and end-of-life management (Jolliet et al. 2015).

2.4.6.1 Data Collection Method

Data collection methods are crucial in gathering information or data for research purposes. It is important to select the most appropriate method based on the research question, the type of data needed, and available resources.

2.4.6.2 Primary Data Collection Methods

The following are some commonly used primary data collection methods:

a. Surveys

Surveys involve asking a sample of individuals or groups to answer questions to gather data. Surveys can be conducted in person, over the phone, online, or through paper forms.

b. Interviews

Interviews entail direct interaction between the researcher and the respondent to gather data. They can be structured, semi-structured, or unstructured, and can be conducted face-to-face or over the phone.

c. Observations

Observational methods involve recording behaviors, events, or activities in their natural setting. This method is useful when researching a phenomenon that cannot be easily manipulated or controlled.

d. Case Studies

Case studies are in-depth investigations of a particular individual, group, or situation, and are useful for gaining a detailed understanding of a particular subject.

e. Experiments

Experiments entail manipulating one or more variables to observe the effects on a dependent variable. This method is useful for establishing causality between variables.

2.4.6.3 Secondary Data

Secondary data involves collecting data from existing sources, such as government statistics, company reports, or academic publications. This method is useful when primary data collection is not feasible or practical.

2.4.7 Software

Using software to perform Life Cycle Assessment (LCA) offers several benefits, including increased efficiency and accuracy in complex calculations and data management, adherence to established LCA methodologies and standards, flexibility for scenario and sensitivity analysis, robust data management, transparent documentation of the LCA process, and access to advanced analysis features. LCA software helps ensure that the LCA results are reliable, standardized, and transparent, making it easier to validate and reproduce the results, communicate with stakeholders, and support decision-making for environmental management.

SimaPro is a widely used LCA software known for its ability to present and interpret inventory and impact assessment results. It was one of the first general-purpose LCA software developed for commercial use. SimaPro offers a user-friendly interface, extensive databases for life cycle inventory (LCI) data, and a wide range of impact assessment methods. It allows users to perform detailed analyses of environmental impacts of products, processes, and systems throughout their life cycles. SimaPro is commonly used in academia, industry, and government sectors for conducting comprehensive LCA studies and making informed decisions based on environmental performance (Batuecas et al. 2019).

GaBi is another popular LCA software that has been widely used since its inception as one of the first general-purpose LCA software. GaBi is known for its flexibility and versatility, allowing users to model complex systems and incorporate nonlinear relationships programmed by the user. It offers a comprehensive database of LCI data and a wide range of impact assessment methods. GaBi is commonly used in industries such as automotive, electronics, and packaging for assessing and optimizing the environmental performance of products and processes, and for supporting sustainability initiatives (Abu et al. 2021).

EASETECH is specialized LCA software for waste management professionals, with features such as waste composition analysis, landfill gas emissions modeling, and waste treatment options assessment (Lodato et al. 2021). Designed to meet the specific needs of the waste management industry for analyzing environmental impacts and optimizing waste treatment processes.

OpenLCA is open-source LCA software with modular features for life cycle inventory modeling, impact assessment, and sensitivity analysis. Allows users to create custom data sets and impact assessment methods but has reported limitations in documentation and calculation accuracy.

SimaPro may be preferred over other LCA software tools like GaBi, OpenLCA, and EASRTECH due to its established usage, comprehensive database, user-friendly interface, robust and flexible modeling capabilities, customization options, support and training options, compatibility with other software, and industry recognition (Mulya et al. 2022). SimaPro is widely recognized and used in academia, industry, and government organizations for its comprehensive features and tools that make LCA modeling and analysis more accessible to users with varying levels of experience. However, the choice of LCA software tool ultimately depends on specific project requirements, user preferences, and budget considerations. The comparison results revealed significant discrepancies in LCA results for various impact categories, such as greenhouse gas emissions, fossil fuel/non-renewable energy, eutrophication, and water depletion. All four software tools, including SimaPro, disagreed with each other at multiple points in the comparisons. These differences were attributed to the varying approaches adopted by each software tool in managing characterization factors (Kulczycka et al. 2015)(Lopes Silva et al. 2019).

2.4.8 Characterization Method

Characterization in LCA assigns values to inventory data to quantify environmental impacts. It involves converting data into impact categories. Methods are established rules based on scientific principles (Mulya et al. 2022). Choice depends on research goals, data availability, and study context. Credible methods ensure reliable results in LCA. Some of credible methods commonly used in LCA studies include ReCiPe (Endpoint and Midpoint), CML 2001, ILCD 2011, TRACI 2.1, IMPACT 2002+, EDIP and USEtox.

2.4.8.1 ReCiPe

The ReCiPe (Relevance and Performance of Life Cycle Impact Assessment Methods) method was initially developed in 2008 through collaboration between RIVM (National Institute for Public Health and the Environment), Radboud University Nijmegen, Leiden University, and Pré

Consultants. It is a widely used life cycle impact assessment (LCIA) method in the Netherlands and Europe for estimating the environmental impacts of products, processes, or services throughout their entire life cycle, from raw material extraction to disposal or recycling.

One of the main strengths of the ReCiPe method is its up-to-date scientific knowledge, as it is regularly updated to incorporate the latest research findings and data. This makes it a robust and reliable tool for assessing environmental impacts. Additionally, ReCiPe provides harmonized characterization factors at midpoint and endpoint levels, allowing for consistent comparison and aggregation of impacts across different impact categories. The updated ReCiPe 2016 version also includes characterization factors that are representative for the global scale, which increases its applicability and relevance for international assessments. Furthermore, ReCiPe 2016 has expanded impact categories, such as impacts of water use on human health, impacts of water use and climate change on freshwater ecosystems, and impacts of water use and tropospheric ozone formation on terrestrial ecosystems, which enhances its comprehensiveness.

However, there are also limitations associated with the ReCiPe method. Data availability and quality can vary depending on the region, sector, or product being assessed, which may introduce uncertainties in the results. Additionally, like other LCIA methods, ReCiPe relies on simplified models and assumptions, which may not always capture the full complexity and variability of real-world systems. Moreover, while ReCiPe allows for implementation of characterization factors at different geographical scales, it may lack the necessary spatial resolution for certain assessments, especially at a local or site-specific level. Furthermore, LCIA methods, including ReCiPe, involve subjective choices such as the selection of impact categories, assignment of characterization factors, and choice of time horizons, which may introduce subjectivity and influence the results (Huijbregts et al. 2016).

2.4.8.2 Comparison of Characterization Method:

ReCiPe, CML, USEtox, ILCD, TRACI, EDIP, and IMPACT 2002+ are all widely used life cycle impact assessment (LCIA) methods for evaluating the environmental impacts of products or systems. Each method has its strengths and limitations, and their suitability depends on the specific context of the assessment (Mulya et al. 2022).

USEtox is a consensus model developed by the United Nations Environment Program and the Society of Environmental Toxicology and Chemistry, which provides globally applicable characterization factors for assessing freshwater eco-toxicity and human toxicity, differentiated into cancer and non-cancer effects. It is currently considered as a possible recommended midpoint characterization model for freshwater eco-toxicity and human toxicity by the European Commission and is under consideration for adoption by several national and international governmental organizations. This makes USEtox a promising choice for toxicity-related impact assessment (Laurent et al. 2011).

ILCD is a life cycle impact assessment (LCIA) method that covers a wide range of impact categories and is based on models and factors used in other widely used methods such as ReCiPe, CML, and USEtox. TRACI is also a popular method that is expected to adopt USEtox as the characterization model for human and eco-toxic impacts. EDIP is known for its comprehensive coverage of impact categories, while IMPACT 2002+ includes specific impact categories such as ionizing radiation impacts on ecosystems and aquatic acidification (Silva et al. 2013) (Owsianiak et al. 2014).

Furthermore, six impact categories in ILCD (climate change, stratospheric ozone depletion, photochemical ozone formation, freshwater eutrophication, marine eutrophication, and impact from ionizing radiation to human health) were based on the models and factors applied in ReCiPe, CML, and USEtox. Different substances were chosen as reference substances for comparison across methodologies, such as ammonia (NH3) for terrestrial acidification and terrestrial eutrophication in IMPACT 2002+, phosphate (PO4 3-) for aquatic eutrophication in both IMPACT 2002+ and ILCD (ReCiPe, CML), and 1,4-dichlorobenzene (1,4-DB) for freshwater eco-toxicity and human toxicity in all methodologies (Laurent et al. 2011).

Selecting the ReCiPe method for life cycle impact assessment (LCIA) due to its robustness, comprehensiveness, consistency with sustainability principles, transparency, availability of data, integration with other assessment methods, and recognition by industry and policymakers. It provides a holistic assessment of environmental impacts across multiple categories, aligns with global sustainability goals, has a transparent methodology and data sources, and is widely accepted in industry and regulatory contexts. After the careful consideration of the specific goals, data availability, and context of the study selecting ReCiPe as LCIA method (Dong and Ng 2014)(Dekker et al. 2020).

2.4.9 Impact Categories

An impact category in LCA refers to a predefined environmental issue or theme used to systematically assess and quantify the potential environmental impacts associated with a product, process, or service throughout its entire life cycle. Impact categories provide a structured framework for organizing and evaluating different types of environmental impacts, such as climate change, air and water pollution, resource depletion, biodiversity loss, and human toxicity, among others. These categories are designed to facilitate the assessment and interpretation of environmental impacts in a standardized and meaningful way. Impact categories are typically quantified using established impact assessment methods or models that convert inventory data, such as energy use, emissions, and resource consumption, into impact scores or indicators. They play a crucial role in identifying environmental hotspots, guiding decision-making, and informing sustainability assessments and strategies for products or processes. It's important to note that the careful consideration of impact categories is essential to ensure accurate and relevant environmental assessments in LCA studies (Huijbregts et al. 2016).

2.4.9.1 Midpoints

The concept of midpoints in Life Cycle Assessment (LCA) is utilized to quantify the environmental impacts of a product or process by identifying intermediate points in the cause-effect chain of an impact category and deriving indicators to measure emissions or extractions. The most studied midpoints in LCA studies are global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and human toxicity potential (HTP), which are included in 95.4%, 74.6%, 69.6%, and 60.0% of studies, respectively. The selection of midpoints in LCA depends on the specific goals of the study, with impacts on the environment (e.g., GWP, AP, EP, and ETP) and human health (e.g., HTP and POP) being commonly used in most scenarios.(Owsianiak et al. 2014) However, resource-related impacts (e.g., ADP, CED, and ADPF) show inconsistent trends in usage, with ADP and CED declining due to a lack of standardization, while ADPF gains relevance as a midpoint for assessing fossil fuels. During midpoint characterization, emissions and extractions are weighted using characterization factors, which represent the relative importance of substance emissions or extractions in the context of a specific midpoint environmental impact category (Dong and Ng 2014). These factors need to be scientifically modeled and quantified in a valid and coherent manner to ensure the accuracy and reliability of LCA results. Kyle Sebastian Mulya did a systemically review and discuss most used Midpoints. It's important to note that the selection of midpoint impact categories depends on the specific goals and scope of the LCA study, and not all categories may be relevant for every assessment.

The midpoint impact categories commonly studied in Life Cycle Assessment (LCA) include: (Icca 2013)

a. Global Warming Potential (GWP)

This category quantifies the potential of a product or process to contribute to global warming by measuring emissions of greenhouse gases, such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), and expressing them as CO2 equivalents.

b. Acidification Potential (AP)

This category measures the potential of a product or process to contribute to environmental acidification by quantifying emissions of acidic gases, such as sulfur dioxide (SO2) and nitrogen oxides (NOx), and expressing them as a common reference, typically sulfur dioxide equivalents.

c. Eutrophication Potential (EP)

This category measures the potential of a product or process to contribute to eutrophication, which is the excessive nutrient enrichment of water bodies, leading to harmful algal blooms and other negative impacts on aquatic ecosystems. It is typically expressed in terms of nitrogen or phosphorus equivalents.

d. Human Toxicity Potential (HTP)

This category measures the potential of a product or process to cause harm to human health through exposure to toxic substances. It may include indicators for carcinogenicity, mutagenicity, and other toxicological endpoints.

e. Photochemical Ozone Creation Potential (POCP)

This category measures the potential of a product or process to contribute to the formation of ground-level ozone, a harmful air pollutant that can damage human health, crops, and ecosystems.

f. Ozone Depletion Potential (ODP)

This category measures the potential of a product or process to contribute to the depletion of the Earth's ozone layer, which protects living organisms from harmful ultraviolet radiation.

g. Resource Depletion Potential (RDP)

This category measures the potential of a product or process to deplete natural resources, such as fossil fuels, minerals, and water, which are used in its production and may not be renewable.

h. Cumulative Energy Demand (CED)

This category measures the total energy demand throughout the life cycle of a product or process, including both renewable and non-renewable energy resources, expressed in terms of a common reference, typically joules or mega-joules.

i. Abiotic Depletion Potential (ADP)

This category measures the potential of a product or process to deplete non-renewable resources, such as minerals and fossil fuels, which are not replenished within a human timescale, expressed in terms of a common reference, typically kilograms or metric tons.

j. Abiotic Depletion Potential Fossil (ADPF)

This category specifically measures the potential of a product or process to deplete fossil fuel resources, expressed in terms of a common reference, typically kilograms or metric tons.

2.4.9.2 Endpoints

The endpoint approach in LCIA methods aims to provide a complete assessment of environmental impacts by simplifying complex impact categories into a few damage categories, making the results easier to interpret. For example, ReCiPe, a widely used LCIA methodology, quantifies human health impacts in terms of disability-adjusted life years (DALY), which considers both years of life lost and years of life disabled due to environmental interventions. Ecosystem impacts are described by species loss in a predefined period, considering emissions to terrestrial, freshwater, and marine systems. Resource impacts are assessed in terms of economic loss caused by the marginal increase in costs due to resource extraction (Dong and Ng 2014).

While the endpoint approach has advantages in terms of interpretability, it may also introduce uncertainties due to the additional modeling steps involved in fate and damage modeling. Therefore, there is ongoing research to develop consistent frameworks that provide LCA results at both the midpoint and endpoint levels, to ensure a comprehensive and reliable assessment of environmental impacts. This highlights the need for further advancements in LCA methodology to improve the accuracy and robustness of endpoint assessments, while also considering the complexities and uncertainties associated with characterizing environmental impacts (Huijbregts et al. 2016).

The Endpoint usually studied in Life Cycle Assessment are explained bellow:

a. Human Health

This impact category focuses on assessing the potential impacts of a product or process on human health. It is commonly quantified using disability-adjusted life years (DALY), which considers both years of life lost (YLL) due to premature mortality and years of life lived with disability (YLD) caused by environmental interventions. DALY provides a measure of the overall burden of disease associated with a product or process, considering both mortality and morbidity impacts.

b. Ecosystem Health

This impact category evaluates the potential impacts of a product or process on ecosystems, including terrestrial, freshwater, and marine ecosystems. Ecosystem health impacts are often quantified in terms of species loss, which represents the number of species that may be lost or affected due to environmental interventions. Species loss is used as an indicator of the potential impacts on biodiversity and ecosystem resilience, reflecting the health and integrity of ecosystems.

c. Resource Depletion

This impact category focuses on assessing the potential impacts of a product or process on resource depletion, including both renewable and non-renewable resources. Resource depletion impacts are typically quantified in terms of economic loss caused by the marginal increase in costs due to resource extraction. This can include impacts associated with the extraction, processing, and depletion of natural resources, such as minerals, fossil fuels, water, and biomass.

2.4.10 Life Cycle interpretation

Life cycle interpretation is a final stage in the iterative process of life cycle assessment (LCA) that involves analyzing and evaluating the results obtained from the preceding stages, including life cycle inventory, life cycle impact assessment, and life cycle improvement. This stage aims to continuously improve the assessment results by assessing them in the context of project goals. If the results are intended for external use in making comparative assertions, such as claims about the environmental impacts of different products, they should be validated through a third-party critical review panel of interested parties. The study results should highlight significant impacts and provide recommendations for reducing material use and environmental burdens (Bilgili and Çetinkaya 2023) (Icca 2013).

Chapter 03: Methodology

In this chapter, the approach employed in our study is described. We conducted a Life Cycle Assessment (LCA) that was aimed specifically at the university's organic waste. At first, we identified the characteristics of this waste. Then, these qualities were measured and statistically categorized using waste and accounting methods. This methodological framework was developed to ensure reliability and simplicity in the interpretation of the results of the research.

3.1 Study Area

The National University of Sciences and Technology (NUST) was established in 1991 and is in the heart of Islamabad having a latitude of 33.6844° N and a longitude: of 73.0479° E, the capital city of Pakistan. It is considered one of the top universities in the country and boasts an impressive 700+ acres of land area. The campus consists of faculties which include residential areas, a shopping centre, a medical centre, banks, dormitories, restaurants and cafeterias, and a wide range of sports facilities such as a gymnasium, tennis courts, basketball and football fields, jogging trails, indoor swimming pools, staff housing units, 17 students' hostels, and numerous academic and administrative buildings. As of the 2021/2023 academic year, NUST has a total enrollment of 6500 students and employs 650 staff members. While almost 70% of the student population and 20% of staff reside on campus, the university campus has an estimated daily population of 6500-7000 people. NUST is primarily focused on teaching, research, and community services. To support these functions, the campus provides academic, administrative, residential, and commercial spaces. Most of the structures on the campus are permanent and built specifically for their intended activities. Figure 3.1 illustrates the geographic location of the National University of Science and Technology (NUST) in Pakistan. The map highlights the province of Punjab, where the university is located, as well as the city of Islamabad.

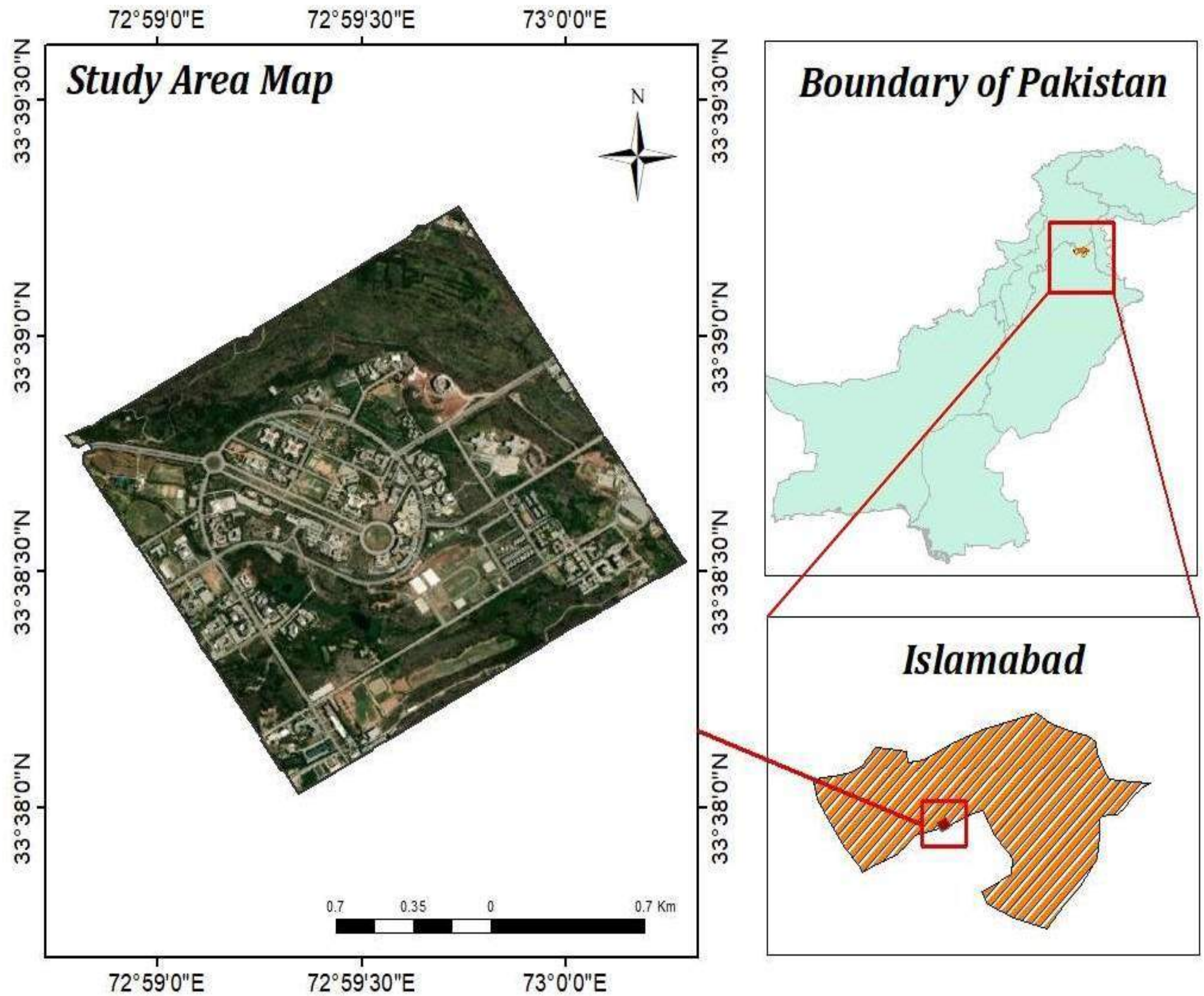

Figure 3.1 Map of the Study Area

3.1.1 Waste Generation Rate at Higher Education Institute

The solid waste generated in university is around 2339 kg, approximately 2 metric tons per day. Almost 1 metric ton per day is organic waste which was taken in this study. Table 3.1 shows the total organic waste generation per year at Islamabad University.

Table 2.1 Organic waste generation per year

Total Population	8000
Total waste	2339 kg/day
Total Organic waste	1264 kg/day
Percentage of organic waste	54%
Per capita generation per day	0.29 kg/person/day
Per capita organic waste generation per day	0.15 kg/person/day
Per capita organic waste generation per year	57.67 kg/person/year

3.2 Data Collection

3.2.1 The University Collection System

The university has contracted a private company for the University Solid Waste Collection. The waste collection team comprises six individuals, and two vehicles are utilized to collect waste from various locations across the university as shown in Figure 3.1. The collection of waste begins at 10 a.m. and concludes at 3 p.m. daily. To ensure efficient waste collection, there are 7 Waste Containers, 28 Dumpsters, and 60 small waste bins distributed strategically near various Educational Departments, Girls/ Boys Hostels, Residency Areas, Cafeterias, Administrative Departments, Central Library, Mosque, Sports Complex, Playing Grounds, among others. The management company has established a two-stage waste sorting system to facilitate waste collection, disposal, and transportation, i.e.: primary and secondary sorting stages. The primary sorting stage involves the initial separation of recyclable and potentially recyclable waste from the dustbin to the truck. In the secondary sorting stage, the remaining recyclable, non-degradable, and composting waste are disposed of openly within the University and sorting is carried out there as shown in Figure 3.2 and Figure 3.3. The organic and non-degradable waste is handed over to the Capital Development Authority (CDA), Islamabad, while the recyclable waste is handed over to the scrap yard.

Figure 2.2 University collection vehicles

Primary Sorting Secondary Sorting

Figure 3.3 Organic waste sorting system

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3.2.2 Sources of Organic Waste

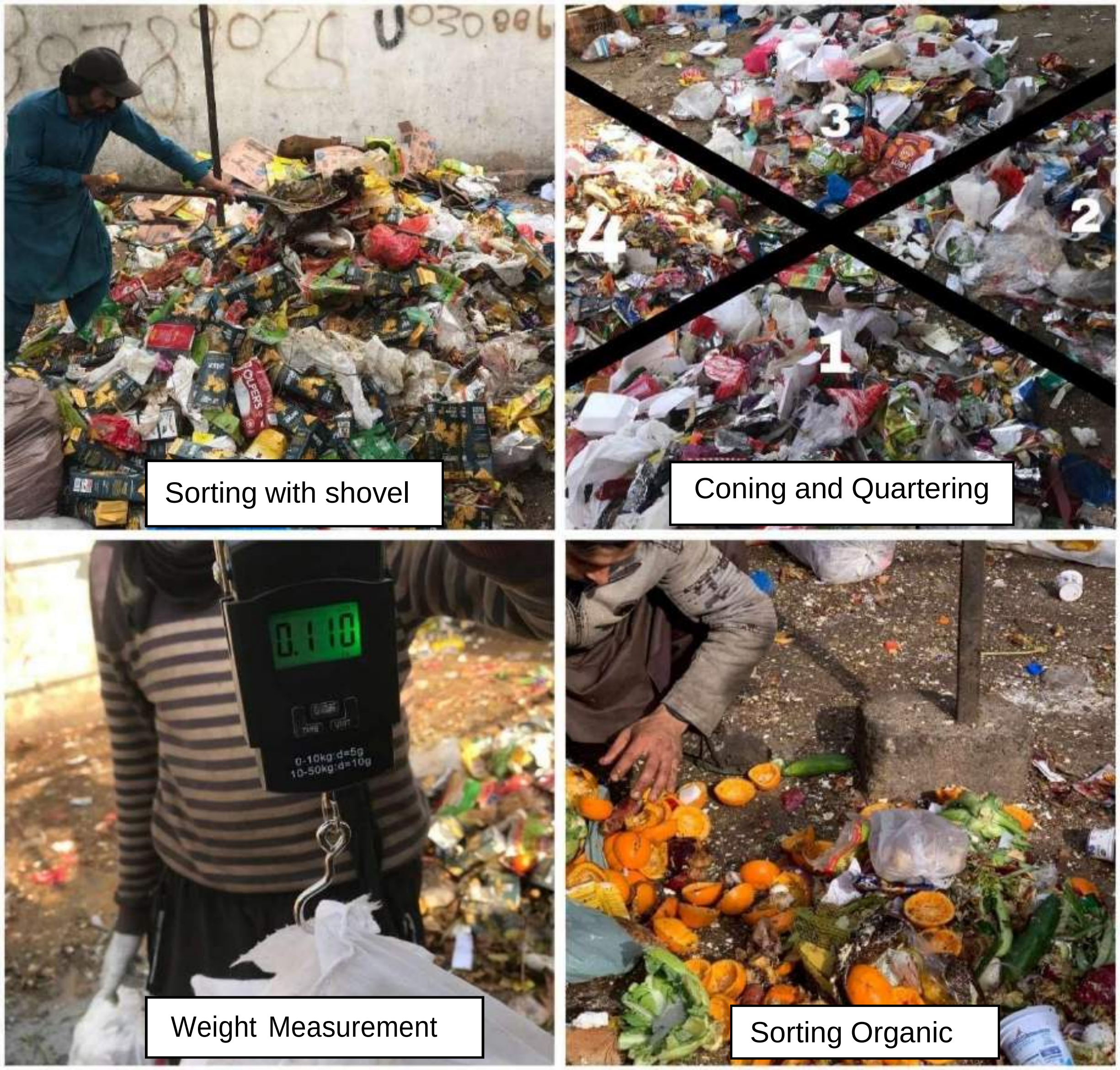
Organic waste primarily comprises three main categories: food waste, paper waste and yard waste. Food waste originates from various sources, including residential areas such as households and domestic units within universities. Additionally, institutional establishments such as hostels and cafes contribute to the generation of food waste. The main source of paper waste is educational departments, administrative offices, and cafes while yard waste is generated from playgrounds. These diverse sources within the residential and institutional sectors collectively contribute to the organic waste stream. Furthermore, yard waste, which encompasses materials like grass clippings, leaves, and branches, also adds to the overall volume of organic waste.

3.2.3 Waste Accounting and Characterization Study

3.2.3.1 Sampling Procedure

The sampling of collected solid waste from various points of the Higher Education Institute was carried out using the ASTM D5231 – 92 (Standard Test Method) and Developing an Integrated Solid Waste Management (ISWM) plan (ASTM International 2008; Modak 2010; Movement and Systems 2014). Using a field-tracking survey method, we manually classified and analyzed the waste generated in 9 different areas over two 5-day waste audits conducted (Waste Audit 1: 17th February 2023 to 22nd February 2023 and Waste Audit 2: 18th May 2023 to 23rd May 2023), representing comparable points during the winter and summer seasons in Pakistan.

The entire waste generated during this period was collected by the university's contractor and aggregated in the university dumpsite. The waste was sorted by Shovel and polythene bags using the ASTM D5231 – the techniques by the sanitary staff, resulting in an average waste sample size of 30-50 kg, which accurately represents the Higher Education Institute Solid Waste. The samples were then manually sorted into each waste category, and the average weights of each component were determined. This meticulous sampling procedure provided precise and reliable data on the characteristics and composition of the solid waste generated by the university, enabling effective analysis and management of the waste.



3.2.3.2 Waste Category

In the waste audit conducted at the University, the waste generated at the university was classified into three primary categories: Organic waste, non-degradable waste and Recyclable waste. Organic waste was further classified into 4 sub-categories, Recyclable waste was divided into 4 sub-categories, while non-degradable waste was divided into 8 sub-categories. A comprehensive description of each sub-category was provided to ensure accurate categorization of waste. This classification system can serve as a valuable tool for waste management and sustainability initiatives at the University. Table 3.2 shows the description of each Sub-category:

Table 3.2 University waste type and category description (Nadeem et al. 2023); (Ugwu, Ozoegwu, and Ozor 2020).

WASTE TYPE	**WASTE CATEGORY**	**DESCRIPTION**
ORGANIC WASTE	Kitchen Waste	Food, bread, vegetables, fruits, rice, etc.
	Yard Waste	Plants, grass, wooden pieces, dry/wet leave, Mud, etc
	Paper(Non-recyclable)	Napkins, Tissue paper, paper towels, wax paper, wrapping paper, Milk/ Juice tetra pack
RECYCLABLE WASTE	Paper (Recyclable)	All office paper, Newspaper, paperboard, tissue boxes, heavyweight folders, books, registers, food packing, empty coffee cups, etc.
	Bottle & Glass (Recyclable)	Coloured/ transparent glass bottles and jars.
	Textile	Fabric, Fabric bags, Cotton, Wool
	Plastic (Recyclable)	All plastic types: PET, food and beverage containers, Plastic cups/glasses, milk jugs, clean grocery bottles, soap bottles, soda bottles, laundry detergent containers, etc.
	Metal (Recyclable)	Metal and tin beverage containers, metal food containers, aluminium foil and containers, cutlery, tins, metal wires, metallic spare parts, etc.
NON-DEGRADABLE WASTE	Plastic(Non-Recyclable)	Plastic Baggies, Styrofoam Containers, Polythene
	Metal (Non-Recyclable)	Paint cans, cardboard & metal mixed container
	Ceramic & Stones	Stone, Ceramic, broken bricks
	Bottle & Glass (Non-Recyclable)	Broken window glass, mirror glass, crystal, etc.
	Domestic hazardous Waste	Safety Eraser, Medicine and acid bottles, etc.
	Sanitary	Diaper, Pads, etc.
	Leather and Rubber	Shoes, Bags, belts, Nylon Etc.
	Miscellaneous	Hairs, bones, waste particles which are difficult to identify, etc.

3.2.3.3 University Waste Composition

The results of the study indicate that the average total waste generated by NUST is 2339.04 kg. Out of this total waste, approximately 54.04% (1264 kg) consists of compost, which includes food waste and yard waste and paper waste, 15.8% (370kg) consists of Recyclable and 30.1% (705kg) consists of non-degradable which widely held entail of plastic. This demonstrates the significant contribution of organic waste to the overall waste stream as shown in Table 4.2 in Chapter 4.

3.3 Waste Treatment Facilities

3.3.1 Open Dumping

The I-12 dumpsite for organic waste disposal has been taken for this study. The total land area considered in this study is 0.186 km^2. It is considered that 1 truck consuming 3 litres of diesel is used to transport all organic waste to the I-12 dumpsite. In this study, all alternative waste treatment facilities were assumed to be taken at the same dumpsite constant of the distance travelled by organic waste.

3.3.2 Landfill

In this study, the landfill we used is Reactive organic landfills, generally referred to as bioreactor landfills, which transform the conventional waste management procedure by proactively stimulating the rapid breakdown of organic waste. In this innovative system, 50% moisture levels are carefully managed, with leachate and occasionally more water injected to maintain ideal conditions for microbial activity. The aerobic decomposition of organic compounds is accelerated significantly by aeration systems. This monitored process not only reduces waste volume and greenhouse gas emissions such as methane CH_4 and CO_2, but it also generates the recovery of 0.1m^3/kg of landfill gas to produce energy.

3.3.3 Compositing

Windrow composting is a popular aerobic decomposition method for organic waste such as paper, yard waste and food scraps. Organic materials are organised into windrows, which are long, thin heaps or rows. These windrows are normally installed outside in a flat area. To break down organic materials, bacteria and fungi require 100kg of oxygen. Aeration of windrows with specialised equipment distributes oxygen, improves microbial activity, and maintains the appropriate temperature range of 50°C to 70°C to optimise decomposition. According to the Ecoinvent database, one kilogram of organic materials in windrows converts into 0.5 kilograms of nutrient-rich compost that may be utilised as a fertilizer.

3.3.4. Anaerobic Digestion

In anaerobic digestion, thermophilic, single-stage digestion with post-composting is a productive waste management method used in this study. It proceeds by processing organic waste materials and putting them to high-temperature anaerobic digestion, generally between 50°C and 65°C, utilizing specialized microbes that break down organic matter into methane and digest it. The biogas produced can be used as a renewable energy source. The digest is post-composted with bulking agents at increased temperatures (50°C to 70°C). According to the Ecoinvent database, the default sludge digester yield is 0.6 kg per kilogram of biodegradable waste, whereas the default figure for biogas generation is 0.1 m^3 per kg of waste. This biogas, produced from biodegradable waste materials, is utilized as a natural gas substitute for heat.

3.4 Life Cycle Assessment

According to ISO 14040-44 (2006), the life cycle assessment for determining a sustainable option for organic waste management in Islamabad's universities considered the recycling of paper and the management of food waste, yard waste and paper waste that is not suitable for recycling, which are the primary materials, from sorting to manufacturing. The management of other waste streams, such as recyclables and non-biodegradables, is neglected because the primary focus of this study was on the organic waste types generated through university residences and small business units. Goal and scope, life cycle inventory, life cycle impact assessment, and life cycle interpretation are the four main stages of the methodology.

3.4.1 Goal and Scope

The goal of this study was to use LCA as a tool to compare different organic waste management methods implemented at University Campus, compare the environmental impact of current scenarios to the proposed scenarios, and determine the most viable management system based on its least impact on the environment. The scope of the study included transportation of the university's organic solid waste, composting, landfilling, and anaerobic digestion. The LCA research has been carried out using SimaPro 9.4.0.3 software and the ReCiPe 2016 methods.

3.4.1.1 Functional Unit

As per ISO 14044 (2006), the functional unit (FU) is a quantified measure of the performance of a product system used as a reference unit. The functional unit chosen for this study is "the treatment of 1 metric ton of Organic waste generated by the university", including resource recovery. This specific functional unit allows for a meaningful and comprehensive assessment of the environmental impacts of various solid waste management methods considered in the study. The results obtained based on this functional unit will be extrapolated to reflect the annual amount of Organic waste currently collected in NUST.

3.4.1.2 System Boundary

The Bin-to-Cradle is a comprehensive as well as efficient approach for evaluating waste management facilities, therefore we have chosen to implement it as the system boundary for our research. The Bin-to-Cradle system boundary includes every stage of the life cycle of a product, from its utilization and waste generation through the end-of-life management and product recovery phases. It also includes the transportation routes for collecting waste from waste facilities. This system boundary enables a comprehensive assessment of the waste management procedure, noting all pertinent phases from the start to the end.

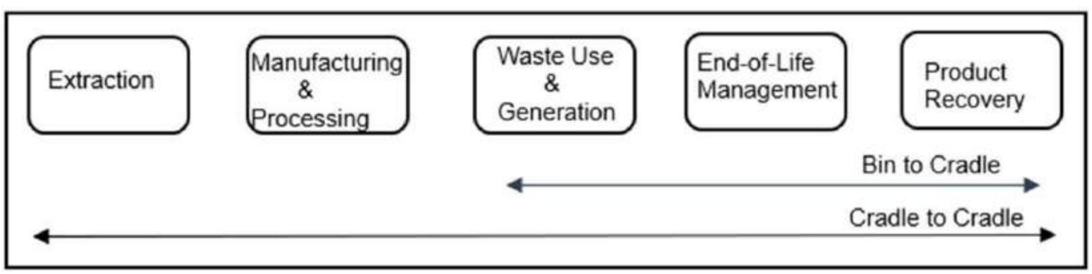


Figure 3.5 Study system boundary

We adopted a system expansion technique in the present study. The foreground and background systems are critical in interpreting the whole impact of waste-related activities in waste management and assessment of the environment. The foreground system represents the major waste management operations, which include waste collection, material sorting, recycling, and different waste treatment methods such as composting and anaerobic digestion. Transportation and waste disposal processes from collecting stations are also included. The background system, on the other hand, includes processes that are only indirectly connected to waste management but are critical to its operation, such as energy generation and raw material production. When determining the system boundaries, factors such as waste composition and quantity, emissions related to waste management operations, and the production of both waste and emissions are taken into consideration.

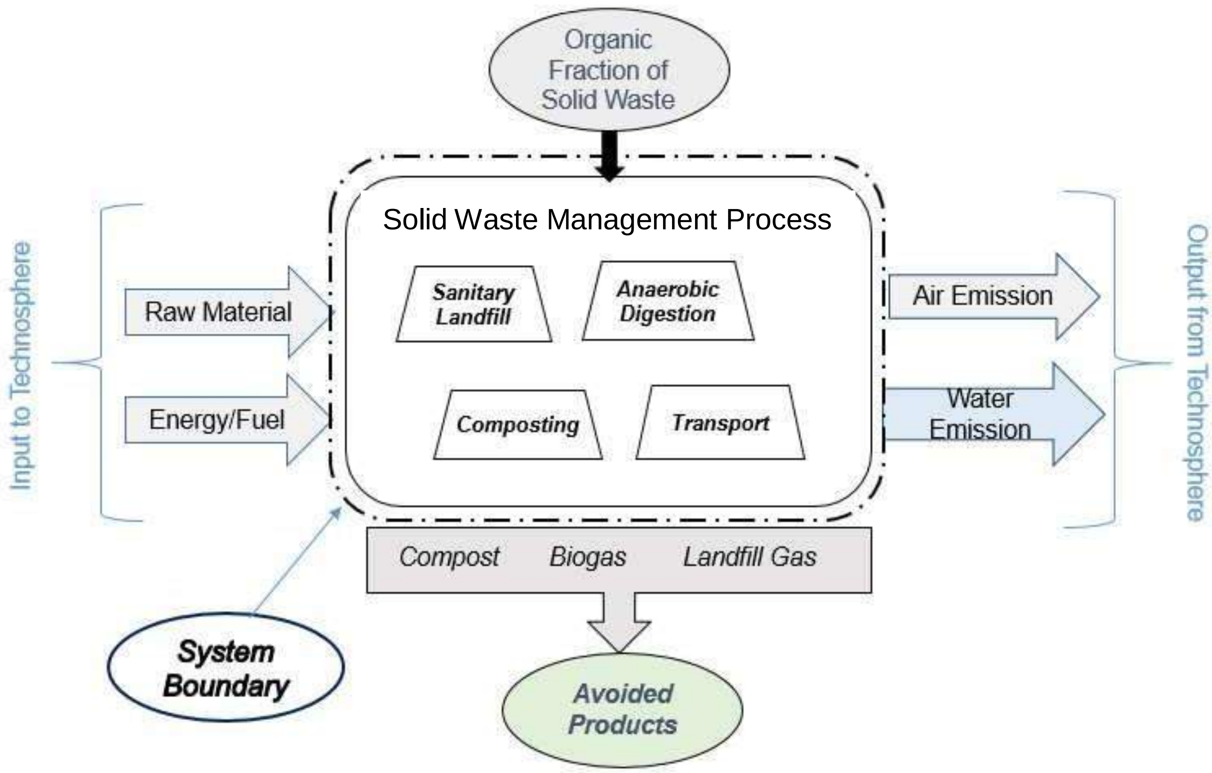


Figure 3.6 System boundary for Organic Waste Management

The SimaPro model-based system boundaries in Figure 3.6 encompass a wide variety of processes and outputs. The boundaries begin with the university's organic waste and go on to include the extraction of raw materials and fossil fuels while taking into consideration the energy used in these extraction procedures. The system boundary includes the different organic waste treatment facilities, such as sanitary landfilling, composting, and anaerobic digestion, as well as waste collection from a single collection point and transportation. The treated organic waste has either become a component of the environment as an emission to air, soil, and water or has been transformed into a valuable product, such as sludge, leachate, compost, biogas, or landfill gas, which exits from the system's boundary as an "*Avoided product*" after the final stage of the system boundary. The phrase avoided products is used since we do not consider it in our System Boundary, but it may still be a commodity utilized in the manufacture of other products and renewable energy.

3.4.2 Scenarios Modeling

To establish the most suitable waste management approach, four scenarios including different waste treatment techniques were considered alternatives for the Business as Usual(present) scenario for the university organic waste management.

3.4.2.1 Scenario 0: Business as Usual – Open Dumping

The business-as-usual scenario is considered the current practice adopted by the university waste management sector. As shown in figure 3.7, after 25.65% of paper recovery from the scavenger at the very start and didn't to the dumpsite thus not consider in our system boundary, the remaining 74.36% of organic waste goes for open dumping without any treatment. The dumpsite located in Islamabad is 12.4km away from the university and a single diesel-powered lorry is used consuming 3 litres per metric ton per day of diesel to transfer the organic waste to the I-12 dumpsite.

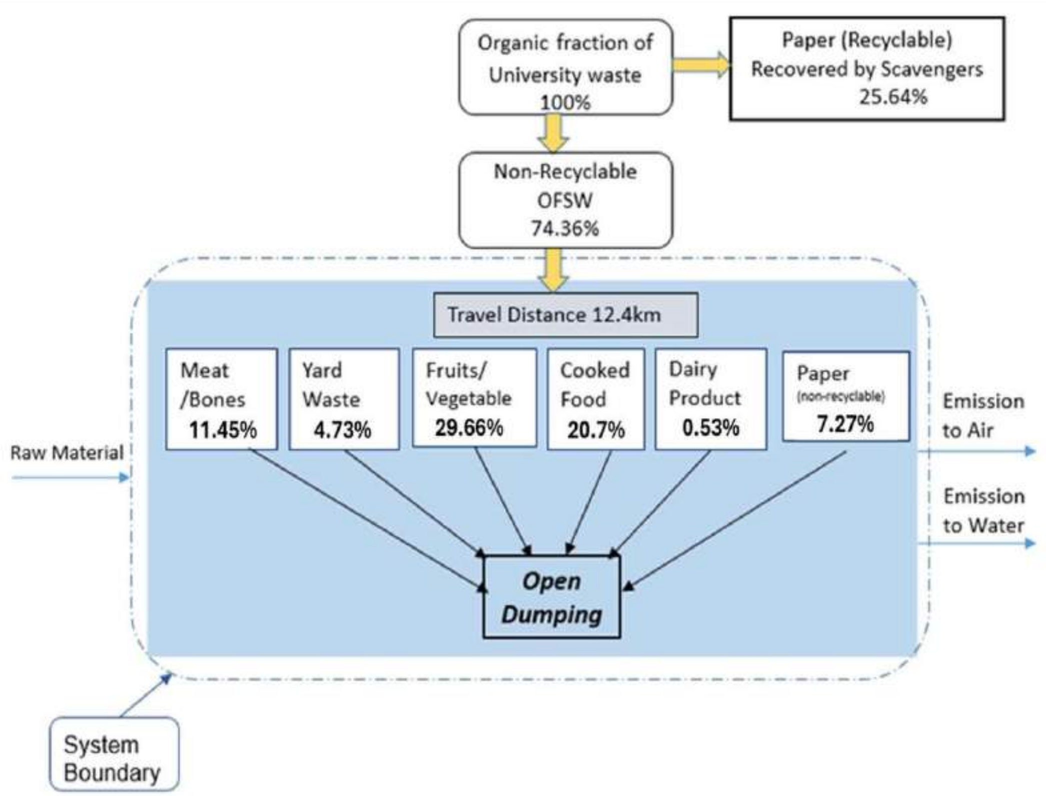


Figure 3.7 Scenario 0_ Open Dumping

3.4.2.2 Scenario 1: Sanitary Landfill

In this scenario, after 25.65% of the paper is recovered by Scavengers at the very start, the remaining 74.36% of organic waste is assumed to have proceeded to a sanitary landfill as shown in figure 3.8. The leachate produced during the process is left untreated which causes emission into the environment. The sanitary landfill has a landfill gas (LFG) collection system, which collects the LFG containing 75% energy and is suitable for use as a natural resource to produce heat.

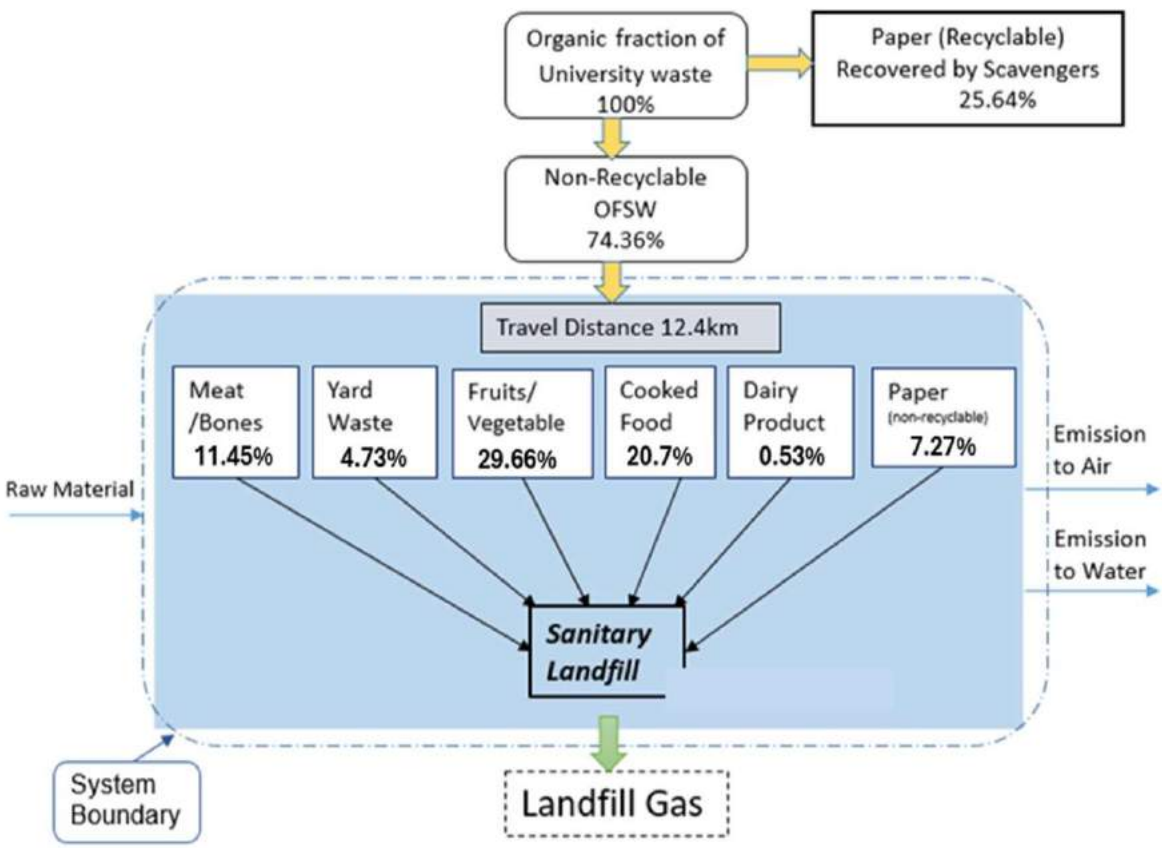


Figure 3.8 Scenario 1_ Landfill

3.4.2.3 Scenario 2 Compositing with Landfill

In Scenario 2, 25.64% of paper waste is recovered by Scavengers and therefore thus not contribute as a damage to environment. 85.75% of organic waste includes leftover cooked food, yard, paper, dairy products and fruit & and vegetables peel waste that undergoes compositing and the remaining

15.43% of leftover meat and bones proceed to the landfill as shown in figure 3.9. Compost is being considered for use as a soil fertilizer.

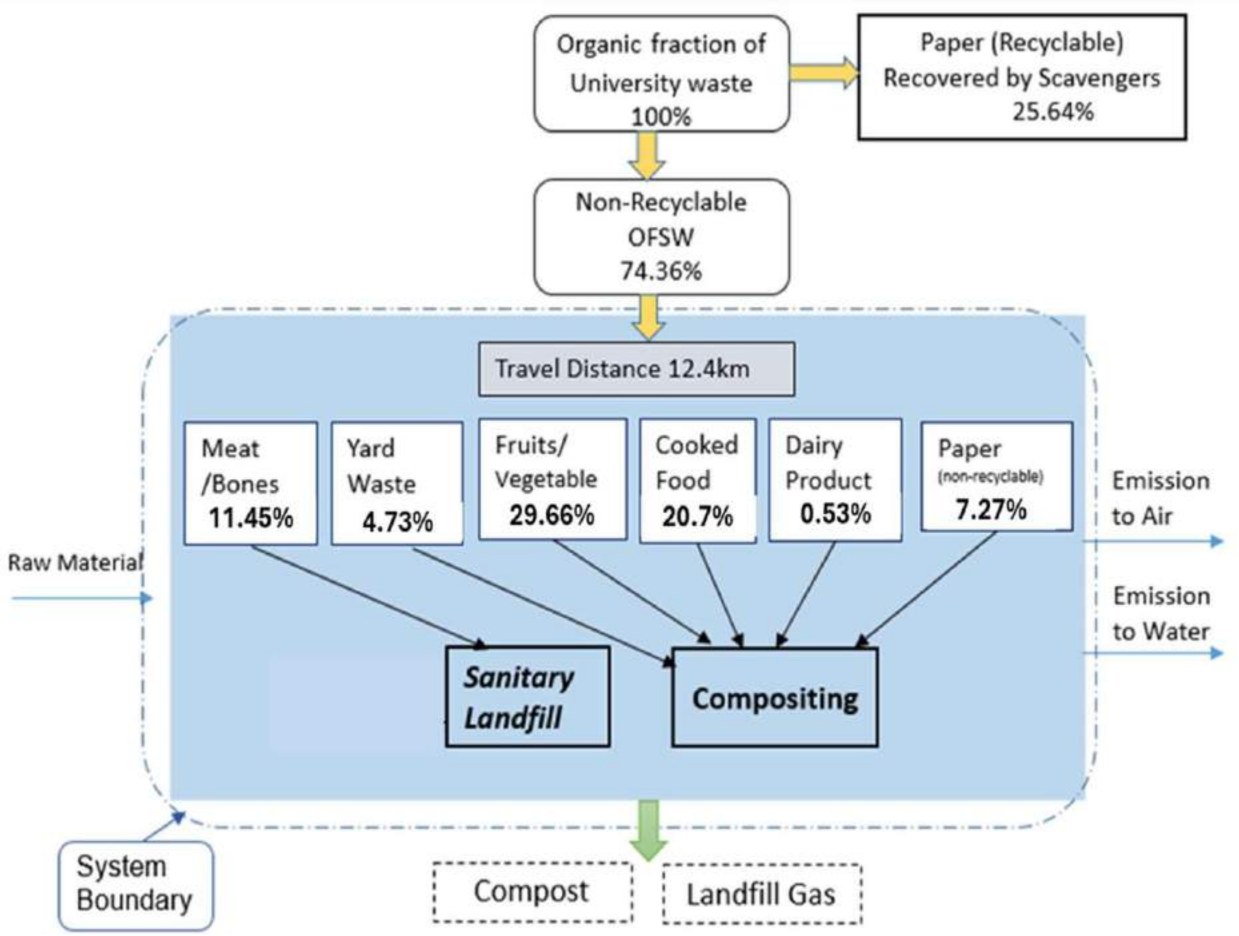


Figure 3.9 Scenario 2_ Compositing with landfill.

3.4.2.4 Scenario 3 Anaerobic Digestion with Landfill

In Scenario 3, 25.64% of paper waste is recovered by Scavengers and not go to any waste treatment technique in system boundary. The 84.57% of organic waste includes leftover cooked food, yard, paper, dairy products and fruits & and vegetables peel waste that undergoes anaerobic digestion and the remaining 15.43% of leftover meat and bones proceed to the landfill as shown in the figure 3.10. The sludge digest formed from an anaerobic digestion plant goes to a landfill and the untreated leachate is generated which causes an impact on the environment The avoided product Landfill gas (LFG) & biogas is being considered as a renewable energy source of natural gas for heating.

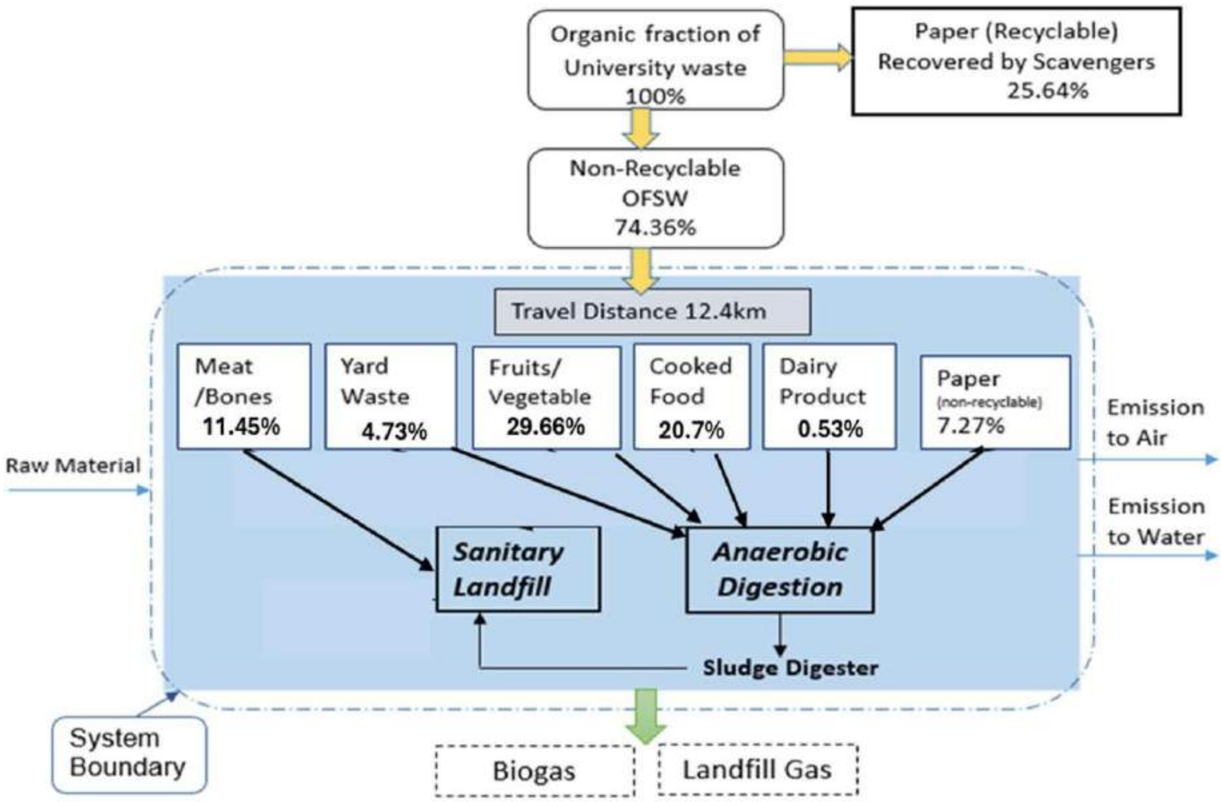


Figure 3.10 Scenario 3_ Anerobic Digestion and Landfill

3.4.2.5 Scenario 4 Compositing, Anaerobic Digestion and Landfill

In Scenario 4, it has been assumed that 25.64% of paper waste is recovered by Scavengers thus not contribute as a damage to environment, 38.42% of organic waste includes leftover cooked food, paper (non-recyclable) and dairy product that undergoes anaerobic digestion, 46.17% is treated by compositing and the remaining 15.43% proceed to the sanitary landfill as shown in the figure 3.11. The avoided product can be used as a renewable energy source or soil fertilizer.

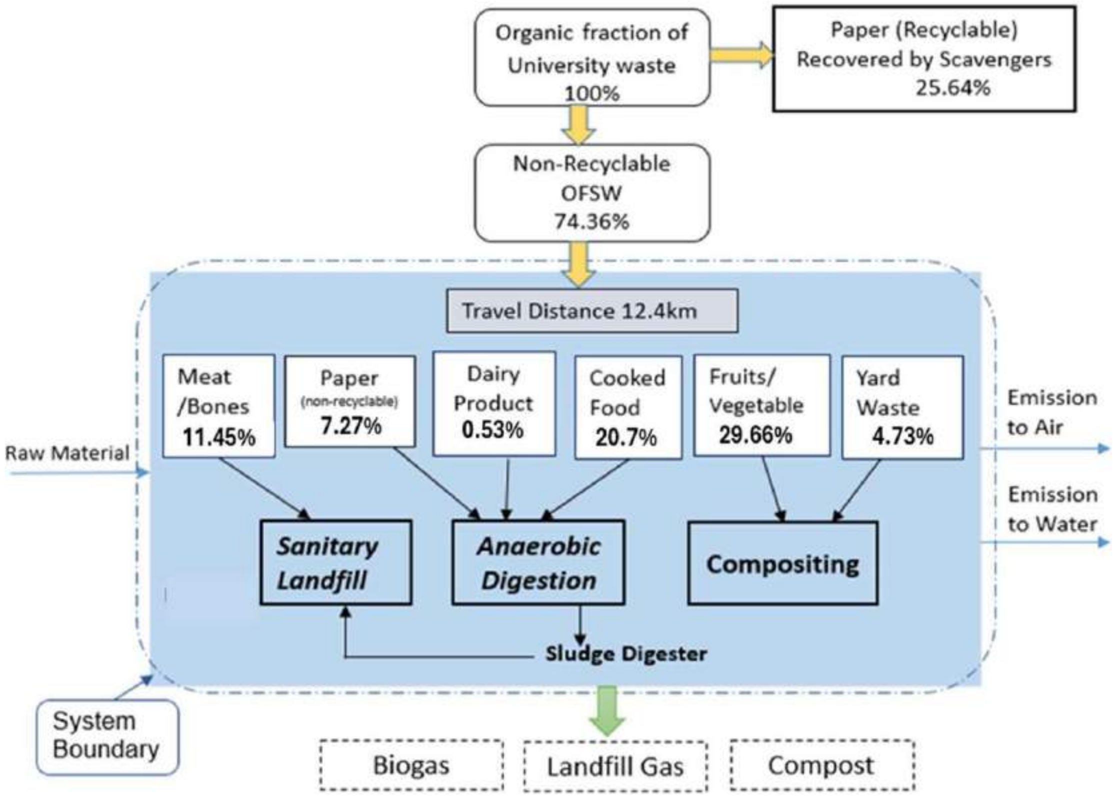


Figure 3.11 Scenario 4_ Compositing, Anaerobic Digestion and Landfill

3.4.3 Life Cycle Inventory

The life cycle inventory, which offers a catalogue of material flows, energy flows, and environmental discharges based on established FU, provides as the foundation for doing an LCA. To initiate, identify all the activities involved in the product's life cycle, from raw material/energy extraction to waste disposal. Second, data on whole processes (i.e., inputs, outputs, and emissions into the air and water) should be gathered directly during the process or indirectly through published literature and databases. In LCA, data collection is the most time-sluggish and complicated project. Third, data are corrected regarding FU.

3.4.3.1 Waste Transport

the organic solid waste's transportation route to the dumpsite located at I-12 is estimated to be 6.2 km one way. The present study includes approximately 12.4 km of distance travelled by waste disposal vehicles from NUST University in Islamabad to waste treatment facilities which are located at the same location of dumpsite as their trip distance. The Ecoinvent database's data for "Freight, lorry 7.5-16 metric tonne, with 3.29t load factor and 9.29t gross vehicle weight" was selected to represent the fuel consumption associated with the transportation of waste and the unit procedure for the transport.

3.4.3.2 Material Input/Output for Life Cycle Inventory

In this study, inputs such as diesel fuel, oil, electricity, transfer distance by machinery, and outputs such as compost, biogas, landfill gas, and so on, as well as emissions to and from the environment, are determined based on the system boundaries. Table 3.3 shows the summary of inventory data mainly obtained from the Ecoinvent database from SimaPro and literature.

Table 3.3 Summary of Inventory data as per Functional Unit (Sivakumar Babu, Lakshmikanthan, and Santhosh 2014[a];Guillaume, Appels, and Kočí 2023[b]; Mandpe et al. 2022[c]).

Waste treatment facilities		**Sanitary Landfill**		**Composting**		**Anaerobic Digestion**	
Parameter	Unit	Input	Output	Input	Output	Input	Output
Diesel [a,b]	L/ ton	6		5.75		5.5	
Area	Km^2				0.186		
			Air emissions				
Ammonia	Kg		1.41E-3		0.7		
Aluminum	Kg		1.45E-4				
Arsenic	Kg		8.46E-9				
Barium	Kg		1.03E-5				
Boron	Kg		4.25E-7				
Cadmium	Kg		3.81E-9				
Calcium	Kg		5.13E-5				
CO_2, biogenic	kg		4.5		220		210
CO_2, fossil	kg		0.205				
CO, biogenic	kg		3.17E-3				
CO, fossil	kg		1.45E-4				
Chromium	kg		1.23E-11				
Cobalt	kg		1.82E-12				
Copper	kg		1.59E-9				
Cyanide	kg		3.95E-5				
Dinitrogen monoxide	kg		3.88E-6		0.0025		0.033
Hydrogen Sulphide	kg		-		0.52		0.089
Iron	kg		2.31E-6				
Lead	kg		5.58E-9				
Magnesium	kg		5.52E-5				
Mercury	kg		5.07E-12				
Methane, biogenic	kg		8.81E-3		1.0		2.4
Methane, fossil	kg		4.03E-4				

Nickel	kg	6.52E-12	
Nitrogen oxide	kg	0.0013	
NMVOC	kg	4.18E-5	
Phosphorus	kg	8.6E-6	
Silicon	kg	4.5E-4	
Tin	kg	1.05E-8	
Vanadium	kg	8.99E-9	
Zinc	kg	2.59E-8	
		Water Emission	
Ammonium, ion	kg	0.631	$9.28E^{-5}$
Aluminum	kg	12.4	
Antimony	kg	2.29E-3	
Arsenic	kg	5.98E-4	
Barium	kg	0.147	
Boron	kg	2.3E-3	
BOD5	kg	18.5	
Bromine	kg	1.18E-2	
Cadmium	kg	0.00116	
Calcium	kg	13.8	
Chloride	kg	5.61	
COD	kg	77.9	
Chromium VI	kg	1,44E-3	
Cobalt	kg	1.28E-3	
Copper	Kg	1.21	
Fluoride	Kg	0.0498	
Hydrogen Sulphide	Kg	0.0748	
Iodide	Kg	3.76E-6	
Iron	Kg	2.13	
Lead	Kg	0.50	
Magnesium	Kg	3.01	
Manganese	Kg	0.25	
Mercury	Kg	1.44E-3	
Nickel	Kg	0.107	
Nitrate	kg	0.068	2.97E-3
Nitrite	kg	0.0344	9.28E-5
Nitrogen, organic bound	kg	1.03	1.09E-4
Phosphate	kg	0.0193	
Phosphorus	kg		7.04E-5
Potassium	kg	1.63	
Selenium	kg	9.04E-5	
Silicon	kg	0.941	
Silver	kg	7.14E-4	
Sodium	kg	4.09	

Sulfate	kg		2.87				
Tin	kg		0.073				
TOP	kg		71.3				
Vanadium	kg		2.65E-3				
Zinc	kg		1.08				
Waste and Emissions to Treatment							
Sludge digest	kg				106.9		620
Waste water	m^3/ton				1.52		1.5
Energy							
Electricity	KWh/ton	0.25		12.82		64.41	
Heat	MJ/ton	0.538				241	
Water [b,c]	L/ton	22.47		9.64			
Avoided products							
Compost	kg				500		
Landfill Gas	m^3/ton		100				
Biogas	m^3/ton						114

TOC: Total organic Carbon, COD: Chemical Oxygen Demand, BOD: Biological oxygen demand

3.4.4 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) phase, which is a vital part of the LCA, aims to comprehend and evaluate the scope and importance of any potential impact on the environment of a process or product. The impact assessment was performed using the ReCiPe 2016 method with midpoint impact categories and endpoint damage assessment along with the LCA software SimaPro version 9.3.0.3 to assess the ecological burdens and benefits. Table 3.4 shows the description of the midpoint impact categories.

Table 3.4 Midpoint categories description (Vlasopoulos et al. 2023).

Midpoint Impact	Unit	Description
Global warming	kg CO_2 eq	Global warming potential (GWP), defined as the integrated infrared radiative forcing a rise in greenhouse gases (GHG),
Ozone Depletion Potential	kg CFC11 eq	The term "ozone depletion potential" (ODP) describes the time-integrated decline in stratospheric ozone concentration over an infinite time horizon.
Ozone formation, Human health	kg NOx eq	The potential for human health ozone formation (HOFP) and the
Ozone formation, Terrestrial ecosystems	kg NOx eq	potential for ecological ozone generation (EOFP) is also included.
Fine particulate matter formation	kg PM2.5 eq	Fine particulate matter production was measured using a human reference intake of PM2.5.

Terrestrial acidification	kg SO2 eq	Inorganic acids released into the atmosphere cause change into acidification
Freshwater eutrophication	kg P eq	The characteristics of freshwater eutrophication depend on what happens to the phosphorus.
Marine eutrophication	kg N eq	Accumulation of nitrogen compound in water overstimulated the plant growth, reducing the level of O_2
Terrestrial Ecotoxicity	kg 1,4-DCB	Human, freshwater (FW), marine, and terrestrial ecotoxicity consequences of chemical emissions. Individual human-toxicological impact factors were developed for both cancerous and non-cancerous. effects
Freshwater Ecotoxicity	kg 1,4-DCB	
Marine Ecotoxicity	kg 1,4-DCB	
Human carcinogenic toxicity	kg 1,4-DCB	
Human non-carcinogenic toxicity	kg 1,4-DCB	
Land use	m2a crop eq	The midpoint characterization elements include relative species loss caused by this use when land is utilised for a given purpose (such as annual or permanent crops, mosaic agriculture, urban land, forestry, or pasture).
Mineral resource scarcity	kg Cu eq	Surplus Ore Potential (SOP), which measures the excess quantity of ore mined per additional unit of resource used, is the midpoint characterization factor for the scarcity of mineral resources.
Fossil resource scarcity	kg oil eq	Referred to as Fossil Fuel Potential (FFP), reflects the ratio between the higher calorific value of a fossil resource and the energy content of crude oil
Water consumption	m3	Different calculations are incorporated for agricultural, industrial, and domestic usage. The quantity of water used.

The endpoint damage assessment category includes Human health, Ecosystem impacts and resource impacts. The midpoints in human health are global warming, human toxicity, stratospheric ozone depletion, ionizing radiation, particulate matter formation, water and resource use. In Resource impact, water use, and resource use will be considered and the remaining factors lie in Ecosystem impacts. Therefore, there is ongoing research to develop consistent frameworks that provide LCA results at both the midpoint and endpoint levels, to ensure a comprehensive and reliable assessment of environmental impacts.

3.4.5 Interpretation

Life cycle interpretation is the final phase of the iterative process of life cycle assessment (LCA), and it includes analyzing and evaluating the data gathered during the previous stages, which include life cycle inventory and life cycle impact assessment. By evaluating the outcomes of the evaluation regarding the project goals, this step aims to constantly enhance them. In the interpretation stage, we will critically evaluate our results to determine Islamabad University's most sustainable waste management strategy. Each strategy's performance will be assessed based on its total environmental impact, highlighting both critical areas and potential parts where improvement is possible. The life cycle assessment's interpretation phase involves one of its components a sensitivity analysis.

3.4.6 Sensitivity Analysis

The sensitivity analysis has been carried out on many variables impacting the system's financial and environmental results. Compositing and anaerobic digestion of organic waste has some degree of uncertainty, but this research makes it easy to identify any potential uncertainties and key factors that might have an enormous impact on the results. Sensitivity Analysis on organic waste for composting and anaerobic digestion was carried out to analyse its impact on the results of endpoint damage assessment categories. Five different scenarios are taken into consideration in the context of the methodology used to conduct the sensitivity analysis. Each assumes a different percentage of organic waste.

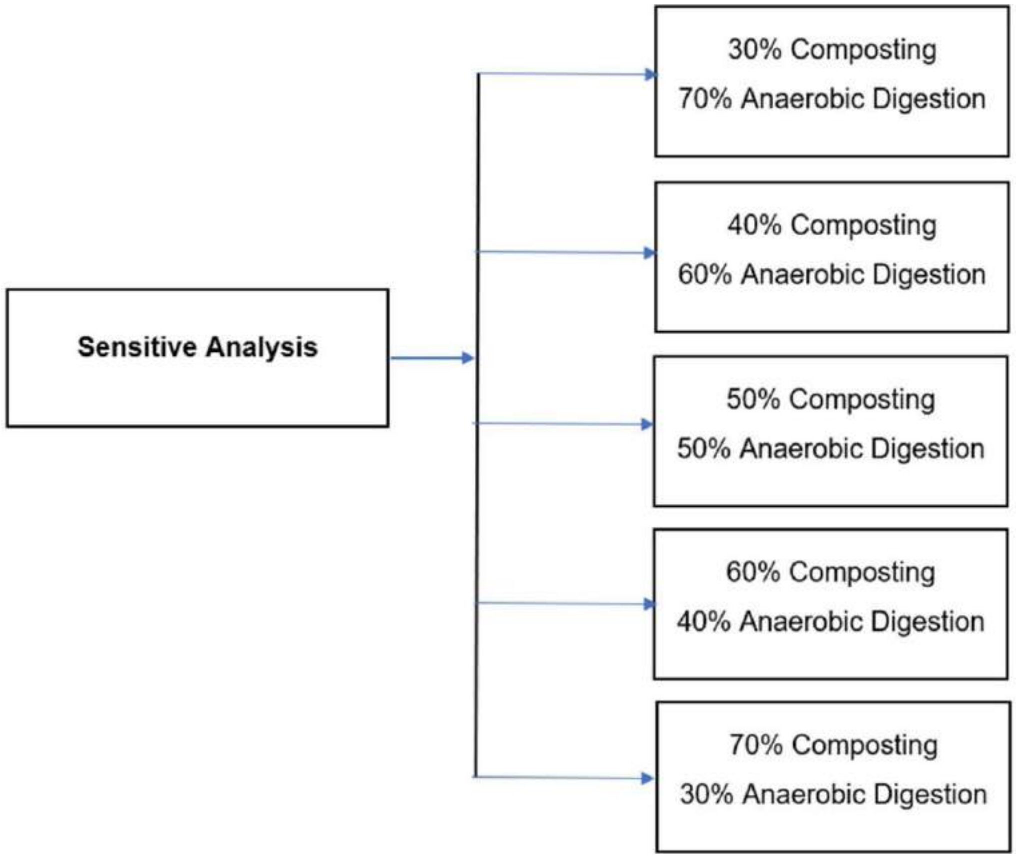


Figure 3.12 Sensitivity Analysis Scenarios

Chapter 04: Results and Discussion

The results of the data analysis are outlined in this chapter, along with a complete analysis and discussion of the results. This chapter should tackle the study's stated research aims and questions. The results are presented clearly and organized using relevant tables, figures, and statistical analysis. Through careful examination and interpretation of the results, this chapter offers insights, explanations, and potential paths for further investigation.

4.1 University Campus Solid Waste Composition

The results of the study indicate that the average total waste generated by university is 2339.04 kg. Out of the total waste generated, approximately 54.04% (1264 kg) is compostable, encompassing food waste, yard waste, and paper waste. This portion of the waste is biodegradable and can be converted into compost through natural decomposition processes. Another 15.8% (370 kg) of the waste consists of recyclables, such as materials that can be processed and reused, thereby reducing environmental impact. The remaining 30.1% (705 kg) is non-degradable waste, predominantly composed of plastics that do not easily break down in the environment. Managing these different types of waste is crucial for sustainable waste management practices, aiming to minimize landfill contributions and promote recycling and composting initiatives wherever possible This demonstrates the significant contribution of organic waste to the overall waste stream as shown in Table 4.1 and Figure 4.1.

Table 4.1 Campus Waste Composition

Category	**Organic Waste**	**Recyclable**	**Non-Degradable**
Percentage	54.04	15.8	30.16
Kilogram	1264.19	369.53	705.318

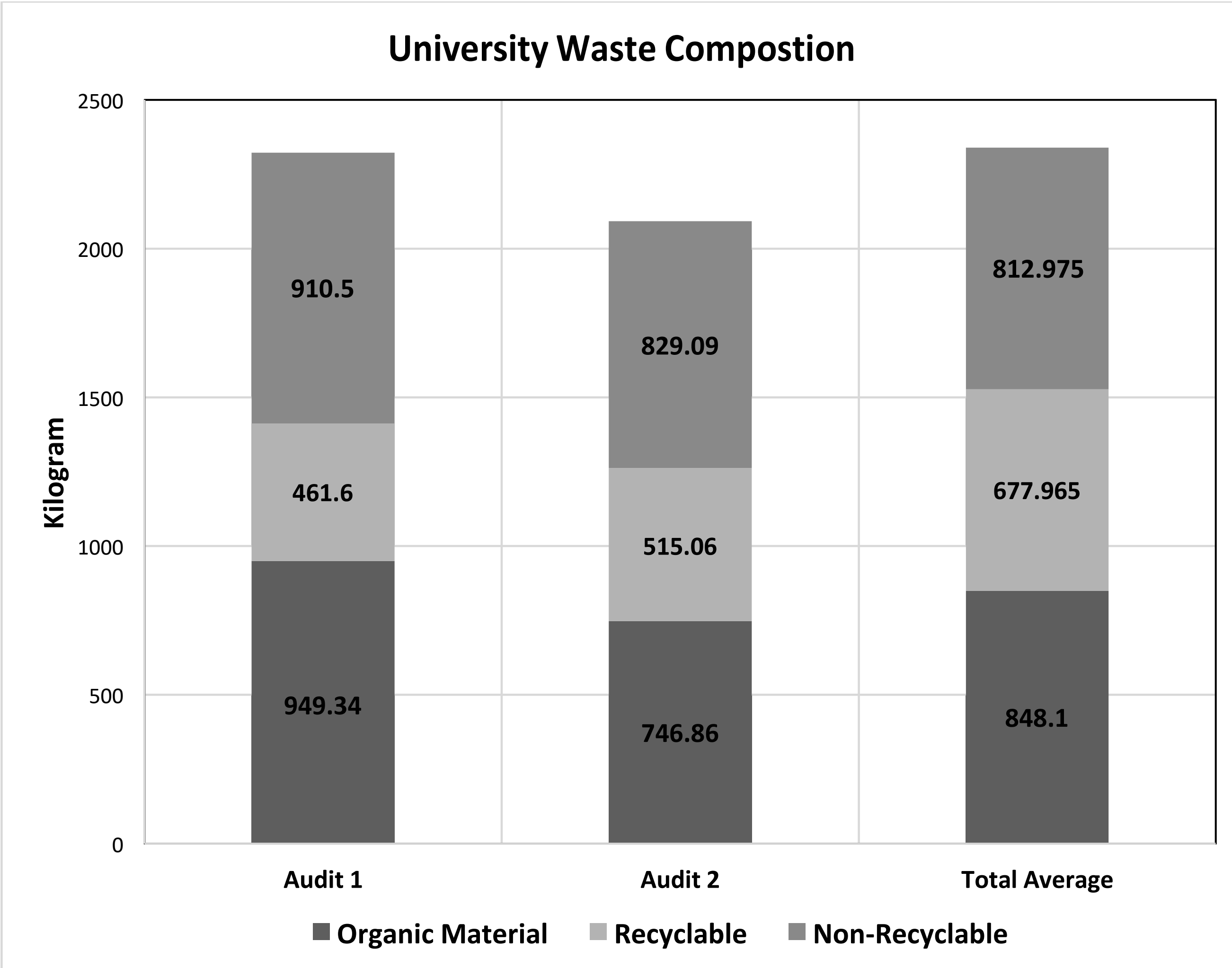


Figure 3.1 Campus Waste Composition in Kilograms

The daily composition of campus solid waste of Audit 1 and Audit 2 is given in Table 4.2 and Table 4.3 as follows:

Table 4.2 Audit 1 Campus waste calculation.

Category (kg)	Organic Material	Paper	Textile	Plastic	Metal	Bottle / Glass	DHW	Ceramic/ Stones	Miscellaneous	Sanitary	Leather/ Rubber
Day 1	842.59	417.18	80.06	324.93	37.95	26.36	20.00	61.76	132.82	94.58	4.54
Day 2	1307.82	582.11	115.12	544.39	62.74	24.94	45.07	101.14	218.59	125.84	5.30
Day 3	915.60	508.48	85.48	292.67	37.47	25.54	13.09	71.38	148.18	104.43	6.50
Day 4	751.07	502.42	59.23	342.41	36.12	31.22	14.15	41.11	117.57	86.82	6.30
Day 5	929.08	506.10	86.52	292.71	50.22	29.62	26.99	72.10	146.47	88.58	6.60
Average	949.23	503.26	85.28	359.42	44.90	27.54	23.86	69.50	152.73	100.05	5.85
Max	1307.82	582.11	115.12	544.39	62.74	31.22	45.07	101.14	218.59	125.84	6.60

Table 4.3 Audit 2 Campus waste calculation.

Category (Kg)	Organic Material	Paper	Textile	Plastic	Metal	Bottle/ Glass	DHW	Ceramic/ Stones	Miscellaneous	Sanitary	Leather/ Rubber
Day 1	743.15	509.76	86.22	435.63	35.42	119.74	12.32	61.59	94.43	28.74	15
Day 2	686.00	480.40	50.40	363.80	43.80	129.60	28.00	86.80	95.20	56.00	18
Day 3	670.29	461.06	60.39	253.02	37.08	103.15	14.09	50.32	64.41	30.19	21
Day 4	933.91	594.89	66.41	482.71	45.48	106.85	34.45	62.26	128.67	37.36	12
Day 5	684.08	453.37	48.79	372.82	55.02	93.36	27.88	45.30	146.37	66.21	11.8
Average	743.49	499.89	62.44	381.60	43.36	110.54	23.35	61.25	105.82	43.70	15.56
Max	933.91	594.89	86.22	482.71	55.02	129.60	34.45	86.80	146.37	66.21	21

Specifically, the study found that food waste had the highest daily average generation among the waste components analyzed. The disposal of biodegradable waste in landfills is linked to various environmental impacts and follows a linear model that is considered unsustainable. Meanwhile, numerous agricultural and urban soils are characterized by low levels of organic matter (Ferretto et al., 2024).Within the university campus, which hosts an estimated population of 65,000 people, daily waste generation averages 2523.76 kg. Food waste emerges as the largest component, comprising 848.1 kg daily, which accounts for 33.6% of the total waste. This includes both pre-consumer and post-consumer food waste. Following closely, recyclable materials, predominantly paper, constitute the second most significant waste category, making up 14% of the total waste with a daily average of 324.153 kg. Plastic waste also contributes substantially, amounting to 438.46 kg per day, representing 18.74% of the waste stream. Other waste types, such as metal, textiles, leather/rubber, and glass/broken bottles, collectively make up smaller proportions, ranging from 2% to 3% each day. Effective management strategies are essential to address these diverse waste components, aiming to reduce overall waste generation, promote recycling efforts, and implement sustainable practices across the university campus shown in Figure 4.2. Table 4.4 in kilograms and percentages.

Table 4.4 University waste composition

Category	**Kg**	**%**
Kitchen Waste	788.2	33.69
Yard Waste	59.90	2.57
Paper (Recyclable)	324.15	13.86
Textile	74.003	3.16
Plastic (Recyclable)	192.46	8.23
Metal (Recyclable)	59.97	2.56
Bottles & Glass (Recyclable)	43.0932	1.84
Ceramic & Stones	36.94272	1.58
Domestic Hazardous Waste	45.6355	1.95
Miscellaneous	63.981	2.74
Sanitary	97.829	4.18
Leather and Rubber	58.289	2.49

Paper (non-recyclable)	91.94232	3.93
Plastic (non-recyclable)	233.1297	9.97
Bottles & Glass (non-recyclable)	144.044	6.16
metal (non-recyclable)	25.467	1.09
Total	2339.039	100

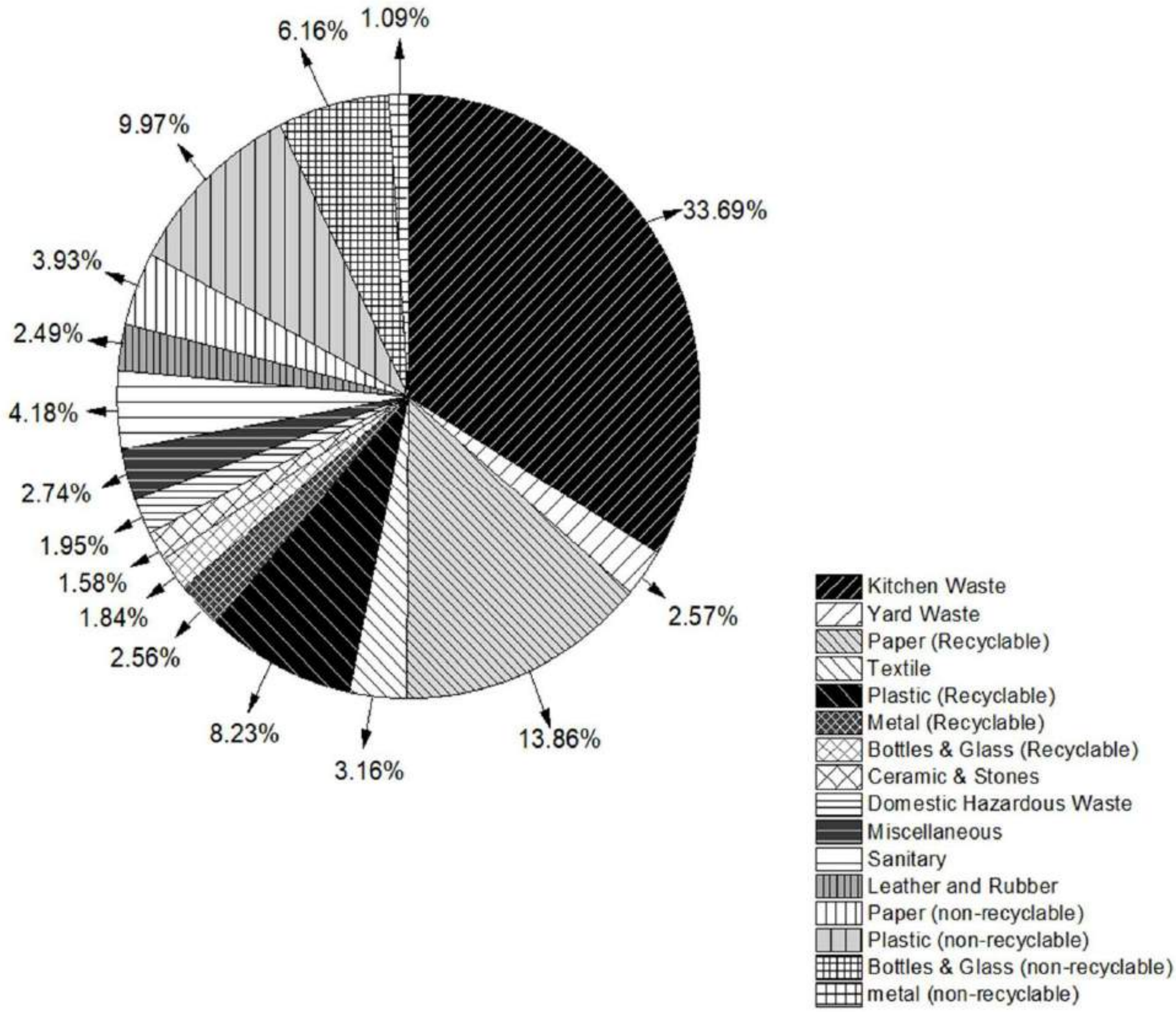


Figure 4.2 University Waste Composition

4.1.1 Campus Organic Waste Composition

The detailed characterization study on organic waste conducted in the institute yielded insightful results. The composition of OFMSW is crucial for its anaerobic biodegradability and influences the microbial communities that break down complex organic compounds into methane (Parvez and Ahammed.,2024).The study identified several primary sources of organic waste generated daily within the institute. Notably, vegetable and fruit peels constitute the largest portion at 29.66%, indicating a substantial amount of food waste from kitchen preparations and consumption. Cooked food waste follows closely, accounting for 20.72% of the organic waste stream, highlighting the significant impact of dining and food services on waste generation. Non-recyclable paper, such as contaminated or soiled paper, contributes 7.27% to the organic waste category, emphasizing the challenge of managing paper waste that cannot be recycled. Yard waste from the institute's outdoor areas also plays a role, comprising 7.11% of the organic waste generated. Moreover, a noteworthy portion of the paper waste generated, totaling 25.64%, is recycled by scavengers, underscoring efforts towards waste reduction through informal recycling channels. Effective waste management strategies targeting these specific organic waste sources are crucial for minimizing environmental impact and promoting sustainability within the institute's operations. According to the Europe 2020 Strategy (EC, 2010), the bioeconomy could provide an important contribution to the achievement of the green targets in Europe in the upcoming decades (Pergola et al., 2018). A basic principle of the bioeconomy is promoting a sustainable and efficient (see e.g. Sepehri and Sarrafzadeh, 2018) resources transformation and conversion into bioenergy and/or bio-based products, reducing the dependency on natural resources (EC, 2012a). The composition graph of organic waste is shown in Figure 4.3.

Table 4.5 Organic Waste Composition

Categories	**Meat/Bone (Leftover)**	**Dairy Product**	**Paper (recyclable)**	**Vegetable/ Fruits Peel**	**Cooked Food (Leftover)**	**Yard Waste**	**Paper (Non Recyclable)**
Percentage	11.45	0.53	25.64	29.66	20.72	4.73	7.27
Kilogram	145	7	324	374	262	60	92

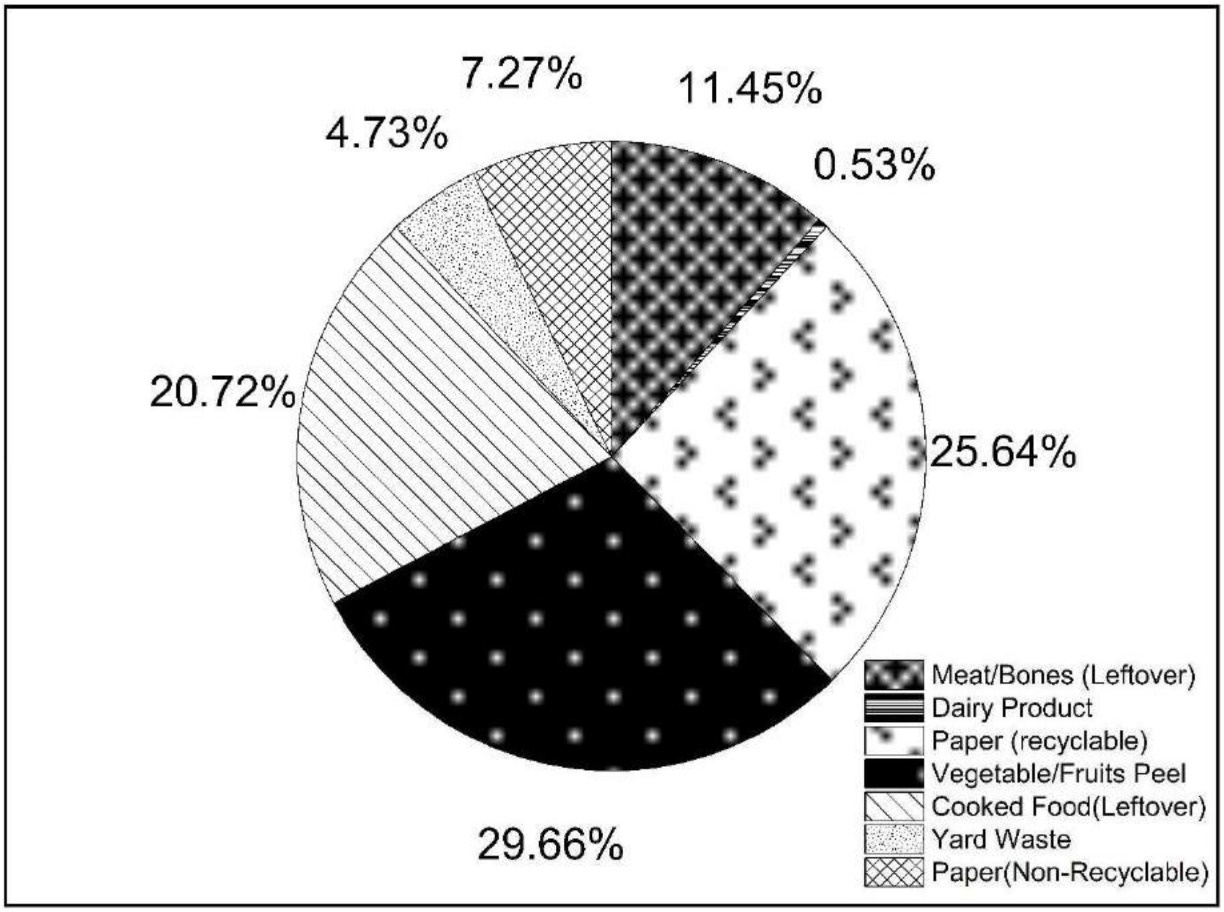


Figure 4.3 Organic Waste Composition

4.2 Characterization Factors

The ReCiPe 2016 method, in Life Cycle Impact Assessment (LCIA), methodologies like ReCiPe (Resource Consumption and Impact Assessment of Products and Environmental Systems) are instrumental in evaluating the environmental impacts of products and systems throughout their life cycles. ReCiPe categorizes impact categories into both midpoint and endpoint levels, providing characterization factors that quantify the potential environmental effects of various activities or substances. Midpoint indicators assess specific environmental mechanisms such as greenhouse gas emissions, acidification, and eutrophication, offering insights into immediate impacts on wellness among people and ecology. On the other hand, endpoint indicators aggregate these midpoint results to assess broader consequences like human health impacts, ecosystem quality degradation, and resource depletion. By employing ReCiPe's comprehensive framework, analysts can discern the full spectrum of impacts of activities or goods on the environment, aiding in informed decision-making towards sustainability and minimizing environmental footprints across industries and sectors (Huijbregts et al. 2017).

4.3 Midpoint Categories

The standard benchmark units are used to measure the midpoint characterization methods. The selected midpoint's abbreviation and units are provided in Table 4.6 according to the goal of my study:

Table 4.6 Abbreviation and Units of selected midpoint

Midpoint Categories	Abbreviation	Units
Global Warming	GWP	Kg CO_2 eq
Stratospheric Ozone Depletion	ODP	Kg CFC^{-11} eq
Fine Particulate Matter Formation	PMFP	kg $PM_{2.5}$ eq
Terrestrial Acidification	TAP	kg SO_2 eq
Photochemical Oxidant Formation: Human Health	HOFP	kg NO_x eq
Freshwater Eutrophication	FEP	kg P eq
Marine Ecotoxicity	METP	kg 1,4- DCB eq
Water Consumed	WCP	m^3
Mineral Resource Scarcity	SOP	Kg Cu eq
Fossil Resource Scarcity	FFP	Kg oil

4.3.0 Comparison of Demonstrated Scenarios

The least sustainable method among the listed waste management practices is the disposal of organic waste in sanitary (Sc-01) and unsanitary landfills (Sc-00) since this has already been mentioned in the literature (Buratti et al. 2015; Liikanen et al. 2018). Methane is the principal driver of global warming in unsanitary landfills, and because there is no emission control system in location, methane is also released straight into the atmosphere. In Scenario 02, the potential for global warming is positively impacted by the avoidance of carbon dioxide and nitrogen monoxide emissions brought on by the production of compost and fertilizer (Mandpe et al. 2023).

Composting reduces methane generation and reduces greenhouse gas emissions by promoting aerobic decomposition. The insignificant fraction that is still dumped in landfills is responsible for the remaining Global warming potential. In Scenario 03, the anaerobic digestion process may catch methane and transform it into biogas, which can be utilized as a source of energy when it is handled properly. Providing an alternative to fossil fuels not only stops the emission of methane into the atmosphere but also reduces the net GWP. Thus, in the context of global warming, it is the greatest alternative for managing organic waste. When waste products, such as biogas, undergo combustion during anaerobic digestion, a significant amount of fine particulate matter (PM2.5) is released into the atmosphere, which harms human health if not treated properly. In business-as-usual situations (Sc-00), huge amounts of leachate and pollutants are released into water bodies as a result of an inadequate system for collecting leachate and other dangerous pollutants, resulting in a severe impact on marine ecology. Terrestrial acidification is the ratio of H+ ion generation per kilogram of a substance to SO_2 (Banar et al. 2009). Acidifying compounds include SO_2, NO_x, HCl, and NH_3. The highest level of terrestrial acidification occurs in the "business as usual" scenario because of significant CO_2 gas emissions as a byproduct of biogas emissions, particularly from the organic percentage of university solid waste. Anaerobic digestion (AD) has a lower value for terrestrial acidification than other waste management options owing to its controlled breakdown process. Organic waste decomposes in the controlled environment of AD without significantly generating acidifying compounds. The process ultimately causes lower nitrogen emissions, especially when compared to aerobic processes like composting, which can produce nitrogen-based compounds like ammonia. Additionally, any by-products that cause acidification, such as hydrogen sulphide, are frequently detected or handled by the AD system. All scenarios, except scenario 01, a sanitary landfill, exhibited a net reduction in terms of stratospheric ozone depletion; nevertheless, sanitary landfilling may emit trace gases during the breakdown of organic waste. Although some compounds, such as CFCs, may not directly deplete the ozone layer, they can, nonetheless indirectly harm the ozone layer through atmospheric processes. Methane emissions and VOCs produced during waste decomposition in sanitary landfills have the worst effects on HOFP. Scenario 03, a combination of transporting the remaining waste to a sanitary landfill and anaerobic digestion of the organic component, produces the greatest results. Scenario 03 has higher water consumption to keep the organic material in the bioreactor wet during the digesting process. The life cycle database for the University of Islamabad at present has been improved by the life cycle assessment of the baseline scenario (Sc-00). In comparison to the baseline scenario, all of the alternative scenarios that were simulated for comparison in the study resulted in a substantial decrease in airborne and waterborne emissions. The avoided products result in a net save during processes. The collection of waste, waste transportation to transfer stations, and the development of treatment facilities all have negligible input in each scenario since all other processes contribute significantly to the scenario, making the transport process seem trivial. The most important effect categories that should be taken into account for alternative methods of managing organic solid waste are marine ecotoxicity and freshwater eutrophication, according to normalization values. Table 4.2 shows the overall results for all waste scenarios included in consideration for this study, as well as comparisons of the sustainability metrics chosen for each scenario separately. The Life Cycle Assessment (LCA) of various scenarios to compare the organic waste solid waste management (OFSM) choices for Islamabad University that have the least negative and most positive environmental effects is presented in the table. Almost all environmental indicators showed that the Business-as-usual scenario (Sc-00) had the greatest environmental impact, followed by Scenario 1 sanitary landfill (Sc-01). Because long-term emissions were taken into account in the study, the results for fossil resource scarcity, Ozone formation, human health, and mineral resource scarcity in these scenarios were much higher. 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 environmental benefits when used to treat organic fractions of solid waste. Anaerobic digestion of food waste has the highest biogas generation efficiency and minimizes environmental burdens, according to a Life cycle assessment of food waste-based biogas generation by (Xu et al. 2015). A Belgian case study on organic fraction of municipal solid waste technologies also declares anaerobic digestion as the best technique for organic fraction waste management (Belboom et al. 2013). Furthermore, an additional research study conducted in Rasht, Iran, compared anaerobic digestion and composting for managing organic waste. The study highlighted the benefits of anaerobic digestion, both in terms of its positive environmental impact and its economic feasibility. This provides additional strong support for the idea that anaerobic digestion is the most advantageous option for handling the organic fraction of municipal solid waste in the region (Behrooznia, Sharifi, and Hosseinzadeh-Bandbafha 2020).

Table 4.7 Results of Midpoint Categories Assessment

Impact category	Unit	Sc-00 (UL)	Sc-01 (LF)	Sc-02 (COM+LF)	Sc-03 (AD+LF)	Sc-04 (COM+AD+LF)
Global warming	kg CO^2 eq	1374.15	750.9	149.9	94.17	127.47
Stratospheric ozone depletion	kg CFC^{11} eq	$6.43E^{-06}$	$5.52E^{-05}$	$2.94E^{-05}$	$-2.29E^{-03}$	$-1.18E^{-03}$
Ozone formation, Human health	kg NO_x eq	0.0947	0.1454	0.0503	-0.437	-0.15
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.0321	0.065	0.145	0.2508	0.19
Terrestrial acidification	kg SO_2 eq	1.119	0.125	0.075	0.03	0.68
Freshwater eutrophication	kg P eq	8.397	2.171	0.359	-0.373	0.0642
Marine Ecotoxicity	kg 1,4-DCB	635.27	567.38	94.62	-20.82	48.15
Marine eutrophication	Kg N eq	0.913	0.822	0.137	0.106	0.0098
Mineral resource scarcity	kg Cu eq	0.039	0.087	-0.209	-1.65	-0.79
Fossil resource scarcity	kg oil eq	4.29	9.96	1.149	-2.65	-0.39
Water consumption	m^3	0.0204	0.306	-0.655	4.929	1.592

4.3.1 Global Warming

The concept of Global Warming Potential (GWP) serves as a crucial metric in assessing the impact of greenhouse gases (GHGs) on climate change relative to carbon dioxide (CO2), which is assigned a GWP of 1 for a specific time horizon. GWP quantifies how much heat a GHG traps in the atmosphere over a certain timeframe compared to CO2. For instance, methane has a GWP of 28-36 over a 100-year period, meaning it is 28-36 times more potent than CO2 in warming the atmosphere over that time span. Nitrous oxide, another potent GHG, has a GWP of 265-298, indicating its potential to trap heat over 265-298 times more effectively than CO2. Fluorinated gases, used in refrigeration and air conditioning, can have GWPs in the thousands or tens of thousands, making them extremely potent contributors to global warming despite their lower atmospheric concentrations. Higher GWP values signify a greater potential impact on global temperatures, which in turn can lead to a range of environmental consequences such as rising sea levels, shifts in precipitation patterns, ocean acidification, and loss of biodiversity. Understanding and mitigating these emissions are critical in addressing climate change and its far-reaching effects on ecosystems and human societies worldwide.

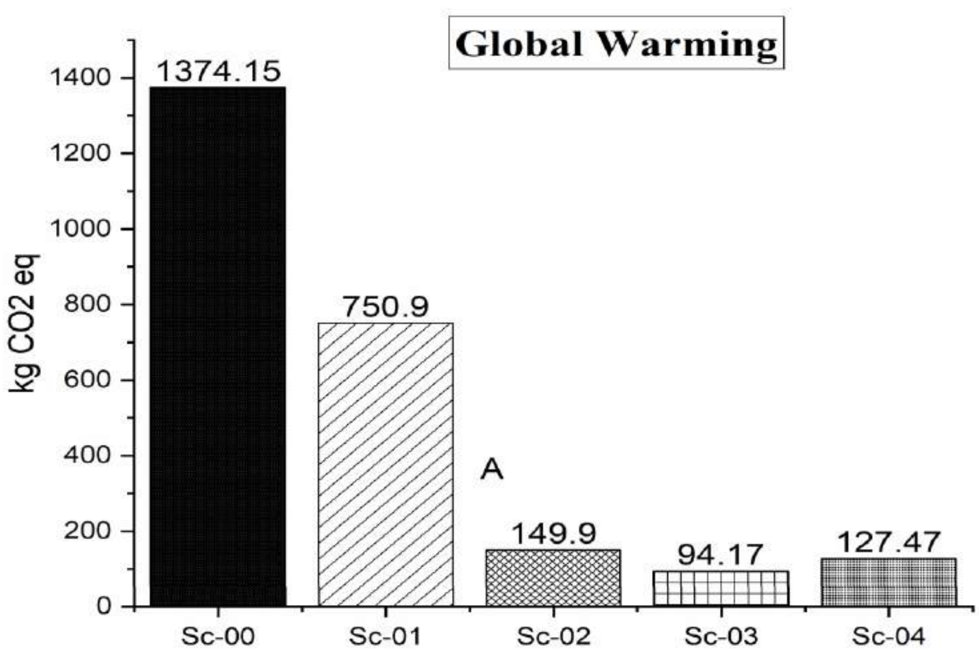


Figure 4.4 Global Warming

The anaerobic breakdown of organic waste in an unsanitary landfill (SC-00) releases a significant amount of methane gas, a potent greenhouse gas (GHG). As a result, unsanitary landfills have the highest GWP values after sanitary landfills (Sc-01), where a significant amount of methane gas is captured and not released to the environment, as shown in Figure 4.4 and Table 4.7. Methane cannot, however, be completely absorbed, resulting in emissions and a significant GWP. Aharoni et al., 2022 conducted a study presenting a unique monitoring system that allows sampling of repetitive samples from within the waste and the unsaturated zone. Despite the considerable heterogeneity observed throughout the profile, the results provided a cohesive and valuable reflection of the evolution of the inorganic nitrogen pool in this highly contaminated environment. The leachates, created inside the waste body, often percolate through the unsaturated zone (also termed- vadose zone) toward the water table. Landfill leachate contamination is generally characterized by a heavy load of dissolved organic matter (OM), inorganic macro-components, heavy metals, and xenobiotic compounds (Christensen et al., 2001). In scenario 02, there is a significant reduction in GWP. When composting is done correctly, the primary emissions produced are CO_2, which has a lower global warming potential (GWP) than methane. Methane emissions are significantly decreased since most of the waste is composted while only 15% ends up in a landfill. Scenario 03 has the lowest impact on GWP due to the process's collection and use of biogas as an energy source, which results in a net reduction in GHG emissions. (Naroznova, Møller, and Scheutz 2016) conduct a study presentation that anaerobic digestion performed well in the terms of global warming potential (GWP) especially when treated the household vegetable waste due to its waste composition and treatment efficiency indicating country-specific guidelines are critical for optimal GWP vindication. In case 04, the combined impacts of AD and composting lower methane emissions, and the diversified strategy is better for GWP.

4.3.2 Stratospheric Ozone Depletion

The ozone layer, crucial for shielding Earth from harmful ultraviolet radiation, faces significant threats from compounds like chlorofluorocarbons (CFCs), carbon tetrachloride, methyl chloroform, halons, hydrochlorofluorocarbons (HCFCs), hydrobromofluorocarbons (HBFCs), and methyl bromide, according to the European Commission (1999). These substances, once widely used in refrigeration, aerosols, and fire extinguishers, have been phased out under international agreements due to their destructive impact on ozone molecules, which leads to ozone depletion in the stratosphere. These industrial chemicals are thought to be a great source of atmospheric pollution since they can bond with other elements and form compounds such as chlorides, oxides, and sulfides (Martínez Flores et al., 2013), all of which contribute to a considerable degree towards ozone destruction based on their varying proportions and depending on a range of factors (Sánchez-Monedero et al., 2010).

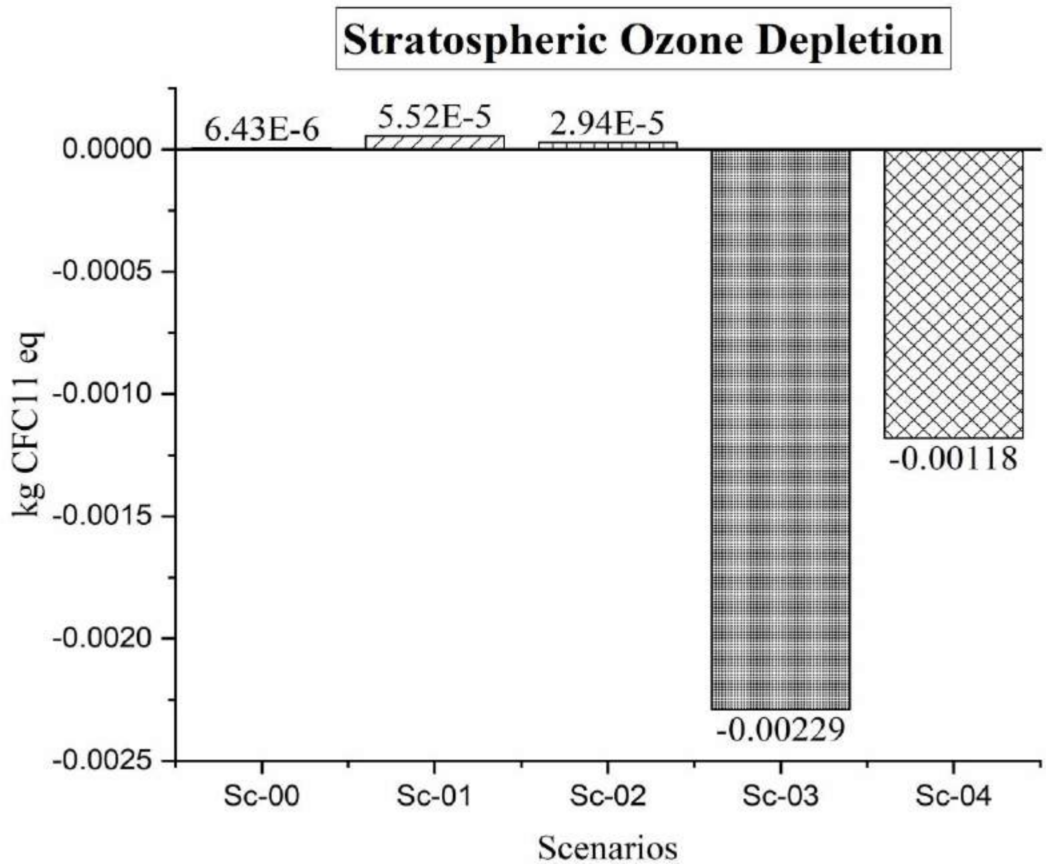


Figure 4.5 Stratosphere ozone depletion.

In scenario 01, the Stratospheric Ozone Depletion Potential is larger than the baseline at 5.52E^{-06} kg CFC^{-11} eq. Due to their anaerobic decomposition environment, sanitary landfills may generate more halogenated compounds (compounds containing bromine, chlorine, or fluorine), mainly if the waste contains products with halogenated organic compounds, as illustrated in Figure 4.5 and Table 4.7. Compared to Scenario 01, this scenario has less landfill proportion, which lowers its ability to deplete the ozone layer. The act of composting alone does not contribute significantly to the destruction of the ozone layer. The value indicates the lower contribution from the reduced landfill component. However, anaerobic digestion scenarios (Sc-03) demonstrated the most significant environmental savings since it has gas gas-captured system installed, they often exclude the production of ozone-depleting compounds. Therefore, anaerobic digesting processes have a lower risk of ozone layer depletion (-2.29E^{-03} kg CFC^{-11} eq) than scenarios requiring sanitary landfilling and composting. The combination of composting and AD reduces the net impact on ozone depletion, demonstrating that this strategy may help reduce the risk of ozone depletion. It appears that implementing efficient waste management procedures at universities may minimize the possibility of ozone depletion.

4.3.3 Ozone Formation

"Ozone formation, impacting human health, refers to the detrimental effects of ground-level ozone production on human well-being. Ground-level ozone is produced when sunlight interacts with volatile organic compounds (VOCs) and nitrogen oxides (NOx), leading to a cascade of chemical reactions. The OH is believed to the one of the major reactive intermediate in the atmosphere. Wilson et al. 2007 provides the chemistry of Hydroxyl radicals with the organic compounds:

$$\text{organic compounds} \xrightarrow[\text{NO}]{\text{OH}} \text{exclusion} + \text{O3}.$$

The route occurring at low NO concentrations typically found in remote (clean) environments. In environmental assessments, the impact of these emissions is quantified using the unit 'kg NOx eq,' which measures the ozone-generating potential of individual compounds relative to nitrogen oxides. This standardized approach helps evaluate the cumulative effects of various pollutants on ozone formation and subsequent health risks, underscoring the importance of controlling VOC and NOx emissions to mitigate their harmful consequences."

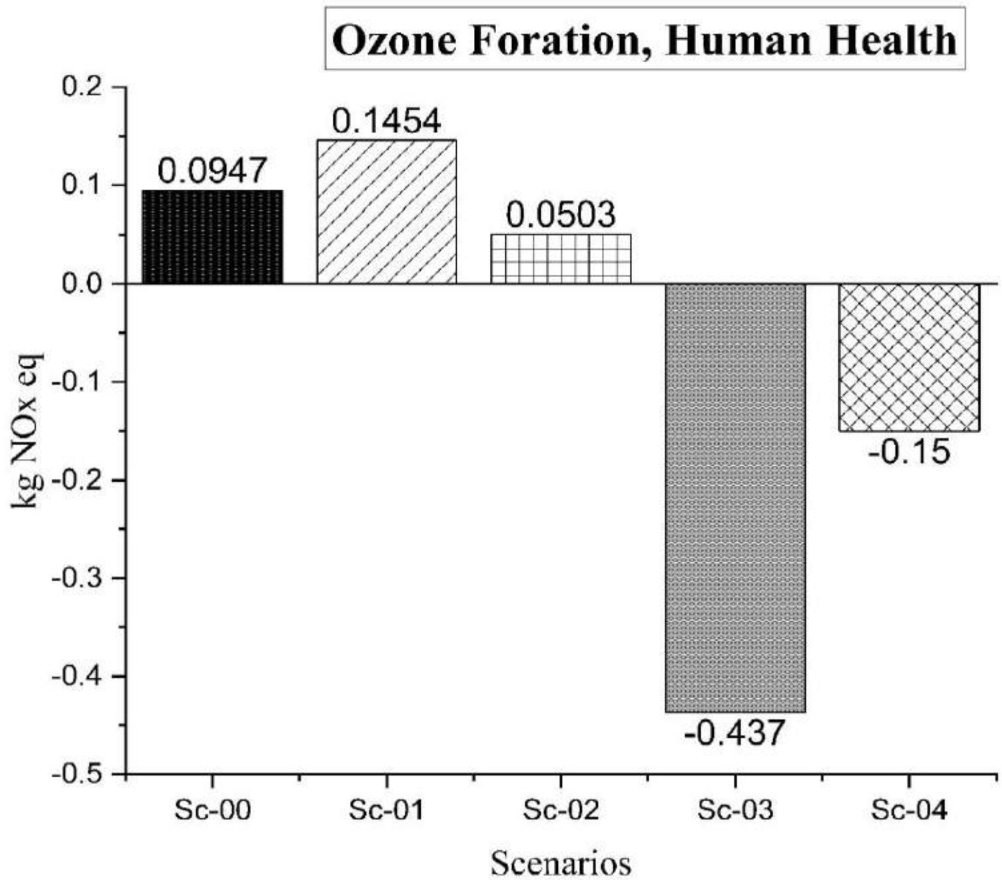


Figure 4.6 Ozone Formation, Human Health

As Shown in Figure 4.6 and Table 4.7, Sanitary landfills (Sc 01) had a somewhat larger impact, releasing 0.1454 kg NO_x eq, probably because of the increased machinery and activities, compared to unsanitary landfills (Sc 00), which had an impact of 0.0947 kg NO_x eq. The distributions and photochemical reactivities of volatile organic compounds (VOCs) from structured industrial emissions have been extensively studied. However, very few have concentrated on the O_3 and SOA production potentials from unorganized sources, including landfills. After analyzing the aromatic chemicals released from Beijing landfills, Liu et al. (2016) calculated the potential for O_3 and SOA generation as 8.86 × 105 and 3.46 × 104 kg•y−1, respectively (Liu et al., 2016). Li et al. (2018) indicated that ethanol, m-xylene, propylene, ethyl acetate, and n-pentane are the main culprits of ozone generation in landfills (Li et al., 2018). Yet, a variety of factors, such as the characteristics of the trash and the weather, influence the volatile organic compounds (VOCs) released from the working surfaces of municipal solid waste (MSW) landfills, leading to notable variations in their emissions (Li et al., 2023). Composting (Sc 02) reduces emissions to 0.0503 kg NOx eq. since it uses natural aerobic processes. Anaerobic digestion (Sc 03) was shown to have a particularly positive impact, with a value of -0.437 kg NOx eq. This can be attributed to its ability to absorb methane and reduce emissions. Finally, an integrated strategy of anaerobic digestion and composting (Sc 04) produced a positive environmental impact, although it was not as good as pure anaerobic digestion, with a value of -0.15 kg NOx eq.

4.3.4 Fine Particulate Matter Formation

Fine particulate matter, commonly referred to as PM2.5, consists of tiny airborne particles derived from diverse sources, including the breakdown and treatment of organic waste. Activities such as composting, waste disposal, and anaerobic digestion contribute to PM2.5 emissions, making it a critical environmental and health concern. Inhaling PM2.5 particles poses significant risks to human health, exacerbating respiratory and cardiovascular ailments due to their ability to penetrate deep into the lungs and even enter the bloodstream. Nanoscale particulate matter can be inadvertently generated through various work processes. Mechanical activities like abrading, sawing, scratching, and shredding contribute to a significant proportion of particulate matter falling within the ultrafine particle range (UFPs), characterized by an aerodynamic diameter of 100 nanometers or less (Buiarelli et al., 2019; López et al., 2022). Beyond health impacts, PM2.5 emissions contribute to environmental degradation by forming smog, which reduces visibility and affects air quality. These particles also have adverse effects on ecosystems and agriculture, influencing plant growth and soil quality. The measurement of PM2.5 emissions is typically expressed in kilograms of PM2.5 equivalent, reflecting their potency and cumulative impact on both human health and the environment. Managing and mitigating PM2.5 emissions are crucial steps in safeguarding public health and promoting sustainable environmental practices across various sectors

According to the spatial position of minerals and pulverized char particles, the minerals in pulverized coal can be divided into two categories: extraneous minerals and included minerals. Different from the extraneous minerals, included minerals are closely combined with char particles, which makes the process of their evolution into fly ash particles more complex, involving coal combustion, mineral coalescence, char fragmentation, and other complex physical and chemical processes (Kobayashi et al., 1977; Quann et al., 1982; Yi et al., 2014; Barta et al., 1992).

In addition, it is also related to the combustion atmosphere (Mohanty et al., 1982; Reyes et al., 1986; Kerstein et al., 1987; Kerstein, 1989). and other factors, making it difficult to understand in detail only through experimental studies. Fine particulate matter ($PM_{2.5}$) primarily forms through the combustion and chemical reactions of various materials.

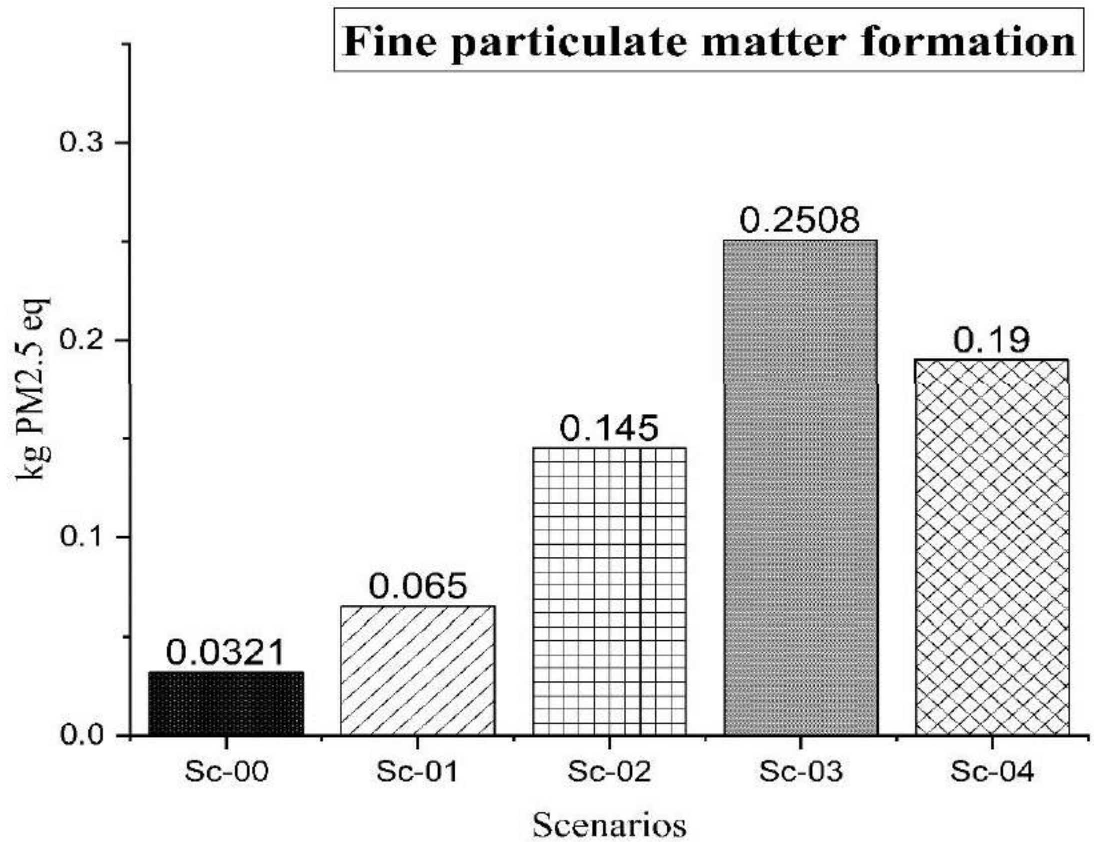


Figure 4.7 Fine Particulate Matter Formation

Fernandes et al., 2023 conducted a study of Portuguese case study on the possibility for producing biogas and biomethane through anaerobic digestion of manure. Their goal was to evaluate Portugal's capacity for anaerobic manure digestion that produces biogas or biomethane. Additionally, it was calculated that Portugal could produce 3561947.05 t of biogas and 1791402.48 t of biomethane annually. In terms of energy, the estimated production efficiencies for biogas and biomethane were 62.96% and 51.82%, respectively. With this metric, it was demonstrated that the environmental impact of PM2.5 emissions varied greatly between Figure 4.7 and Table 4.7. Given the rudimentary nature of such locations, the baseline scenario, in which organic waste is disposed of in an unsanitary landfill, provided a remarkably low PM2.5 emission of 0.0321 kg PM2.5 eq. However, using sanitary landfills—which are meant to keep trash out of the environment—revealed a higher emission value of 0.065 kg PM2.5 eq. This is most likely due to the methane control systems, dust from waste treatment, and mechanical functioning. Composting strategy's mechanical operations and organic material breakdown resulted in much higher emissions, 0.145 kg PM2.5 eq. Focusing on scenario 03, AD for the organic waste resulted in even higher PM2.5 emissions, which reached 0.2508 kg PM2.5 eq. Preprocessing of organic waste and burning of biogas were two of the AD process's processes that contributed to this growth. Divide waste management over many strategies for potential synergistic benefits or efficiency; this is demonstrated by the mixed strategy with both AD and composting and an observed emission of 0.19 kg PM2.5 eq.

4.3.5 Freshwater eutrophication

Human activities significantly increase nitrogen (N) emissions into freshwater, leading to severe eutrophication and its associated impacts (Dong et al., 2023). With the swift pace of urbanization (Bhadane et al., 2022; Musa et al., 2022), the increased nitrogen (N) input into water systems from human activities has been identified as a clear connection between human disturbances and ecosystem impacts (Chen and Wen, 2023; Dong and Xu, 2020; Erisman et al., 2013). Eutrophication from excessive nutrient levels can result in rapid algal growth, leading to oxygen depletion, shifts in species and food webs, and various physical and physiological effects on other organisms due to the proliferation of nuisance algae, such as the production of cyanotoxins (Glibert and Burford, 2017; Morelli et al., 2018; Wurtsbaugh et al., 2019).The metric of eutrophication potential quantifies the propensity of substances to contribute to nutrient enrichment in water bodies, particularly through phosphorus (P) and nitrogen (N) inputs. Excessive nutrients fuel the overgrowth of algae and aquatic plants, triggering harmful algal blooms that disturb aquatic ecosystems. As these blooms decompose, oxygen levels in the water decrease, creating hypoxic or anoxic conditions that threaten aquatic life. Eutrophication diminishes water quality, impairs recreational activities, and can lead to fish killings and biodiversity loss. Scientific methodologies employ life cycle assessment (LCA) frameworks and impact assessment models to evaluate a substance's potential to cause eutrophication, typically expressed as the amount of phosphorus (P) equivalent to one kilogram. These assessments inform strategies to manage nutrient inputs, promote sustainable agricultural practices, and safeguard freshwater ecosystems against the detrimental effects of eutrophication.

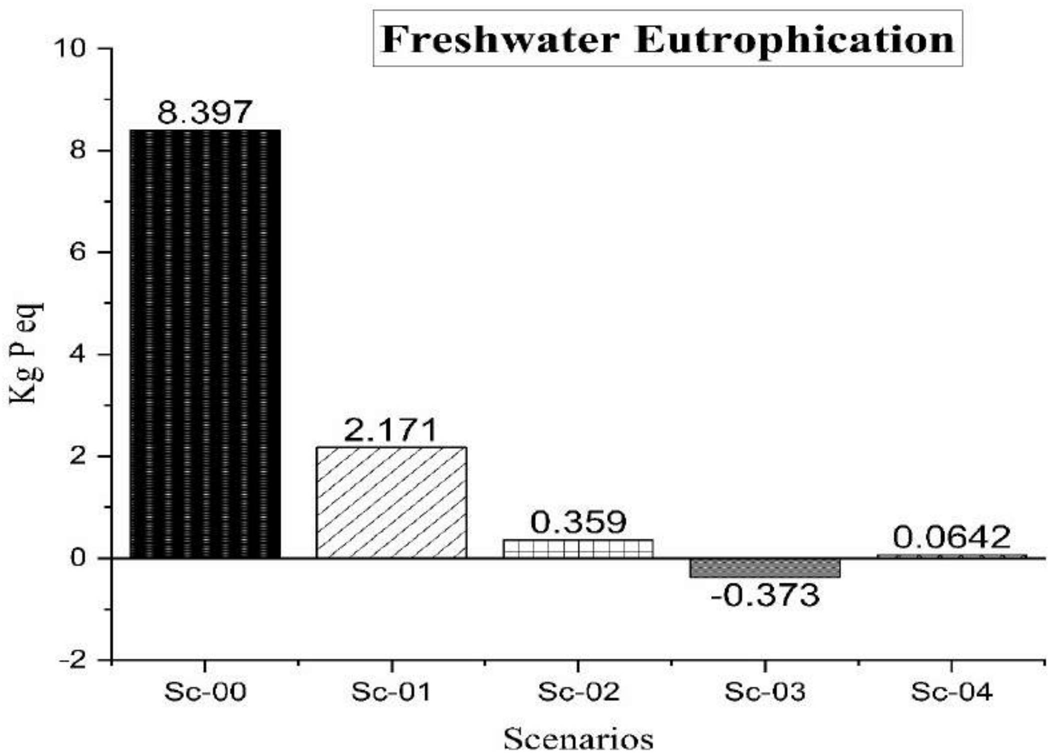


Figure 4.8 Freshwater Eutrophication

River watersheds exported four to six times more dissolved inorganic nitrogen (DIN) than they did during the preindustrial era, while human actions mobilized more than twice as much nitrogen as natural processes (Galloway et al., 2004). (Galloway and Cowling, 2002; Green et al., 2004). The increased anthropogenic N input to water systems due to urbanization's rapid growth has been established as a clear link between human disruptions and ecosystem consequences (Bhadane et al., 2022; Musa et al., 2022; Chen and Wen, 2023, Dong and Xu, 2020, Erisman et al., 2013), whereby eutrophication brought on by an abundance of nutrients can cause algae to grow quickly, oxygen depletion as a result of an increase in algae, species and food webs to shift, and nuisance algae to have a physical and physiological impact on other organisms, such as the production of cyanotoxins (Gilbert and Burford, 2017, Morelli et al., 2018, Wurtsbaugh et al., 2019). Naturally, as the lake matures and sediment fills in the aquatic system, eutrophication happens over decades. However, human activity has accelerated the rate and magnitude of eutrophication in aquatic ecosystems through point-source discharges and non-point loadings of limiting nutrients, such as phosphorus and nitrogen. This has had disastrous effects on aquatic life and drinking water sources, as well as recreational water bodies (Zhang et al., 2023; Knight, 2021).Scenario 00 had the largest potential for eutrophication, measuring 8.397 kg P eq. This was most likely the result of nutrient-rich leachates entering water bodies, as shown by the high content of phosphate and nitrate, as shown in Figure 4.8 and Table 4.7. In evaluating the eutrophication potential of waste management scenarios, significant reductions were observed due to varying treatment methods. Scenario 01, employing a sanitary landfill with improved waste containment and reduced leachate contamination, achieved a reduction in eutrophication potential to 2.171 kg P eq. This reduction was further enhanced in Scenario 02, where composting techniques facilitated aerobic decomposition, lowering the eutrophication potential to 0.359 kg P eq. Notably, Scenario 03, focusing on anaerobic digestion, demonstrated the most substantial reduction with a negative value of -0.373 kg P eq, indicating a net environmental benefit potentially attributed to nutrient absorption or transformation into valuable byproducts like nutrient-rich digest.

The combined approach in Scenario 04, integrating composting with anaerobic digestion, synergistically minimized eutrophication potential to 0.0642 kg P eq. This underscores the complementary nature of aerobic and anaerobic processes in effectively mitigating nutrient release into the environment. These findings highlight the importance of waste management strategies in reducing eutrophication impacts, emphasizing the potential benefits of aerobic decomposition in preventing nutrient leaching and the transformative capabilities of anaerobic digestion in converting pollutants into environmentally beneficial outputs. Scientific assessments utilizing life cycle analysis and impact assessment models are pivotal in quantifying and optimizing these environmental benefits across different waste management scenarios.

4.3.6 Marine Ecotoxicity

The damage that pathogens in the waters bring to marine life is known as marine ecotoxicity. Such toxins, some of which accumulate in higher proportions up the food chain, can harm aquatic organisms directly or cause long-term impacts on the environment. 1,4-Dichlorobenzene (1,4-DCB) is used as a benchmark for comparing the relative ecotoxicity of various substances.

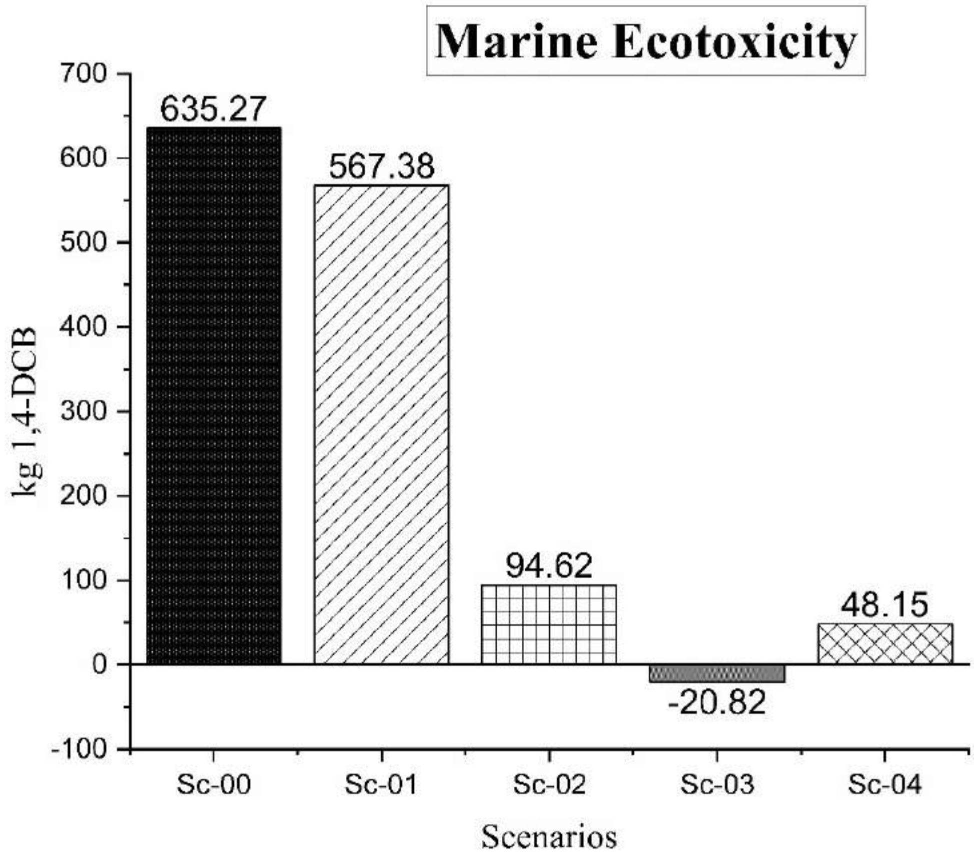


Figure 4.9 Marine Ecotoxicity

Yidong et al.,2012 conducted a study on the effectiveness of a rural filthy landfill's leachate treatment system using a multi-soil layering system (MSL). To study the treatment of landfill leachate without aeration or with a low aeration supply, the researchers used four MSLs with altered soil mixed blocks (SMB) and varied hydraulic load rates (HLR). The outcomes of the trial showed that the enhanced MSL could successfully treat P, NH4–N, and chemical oxygen demand (COD). Under HLRs of 200 and 400 L/(m2·d) without aeration, MSL's COD and NH4–N removal efficiencies were 97.4%, 82.4%, 72.0%, and 62.0%, respectively; under intermittent aeration, M800 and M1600's COD and NH4–N removal efficiencies were 62.3%, 53.4%, and 45.3%, 35.3%, respectively. Strong nitrification led to low N removal efficiency, and at the end of the trial, the MSL's capacity to remove nitrogen had significantly decreased. P removal effectiveness of MSL under HLR 200 and 400 L/(m2·d) ranged from 75.6% to 91.9%. When MSLs became clogged due to HLRs of 800 and 1600 L/(m2·d), occasional aeration helped to clear the blockage. As an attractive nitrifying biofilm reactor, MSL shows promise. Figure 4.9 and Table 4.7 show indicates the largest impact is caused by disposing of garbage in an unsanitary landfill (Sc-00), which produces 635.27 kg of 1,4-DCB equivalent, because of poor management and environmental controls. Transitioning to a sanitary landfill (Sc-01) reduces this impact to 567.38 kg 1,4-DCB equivalent because of enhanced infrastructure and leachate control. There are even greater reductions in Scenario 02, when most organic waste is composted, with an impact of 94.62 kg 1,4-DCB equivalent. The case that has the least negative effects on the environment, Scenario 03, employs anaerobic digestion to get rid of the waste, which has a net positive impact on the environment of -20.82 kg 1,4-DCB equivalent. An integrated strategy of anaerobic digestion and composting produces an impact of 48.15 kg 1,4-DCB eq in Scenario 04, highlighting the advantages of varying waste treatment methods.

4.3.7 Marine Eutrophication

This metric is generally brought on by the over-release of nutrients (mainly nitrogen and phosphorus) into freshwater or marine ecosystems, which promotes excessive growth of plants and algae, or "algal blooms". This could reduce the water's dissolved oxygen content, hurting aquatic life and the water's general quality. Considering that nitrogen molecules like nitrate and ammonia are frequently to blame for eutrophication, the unit used in our study (kg N eq) refers to the equivalent kilograms of nitrogen.

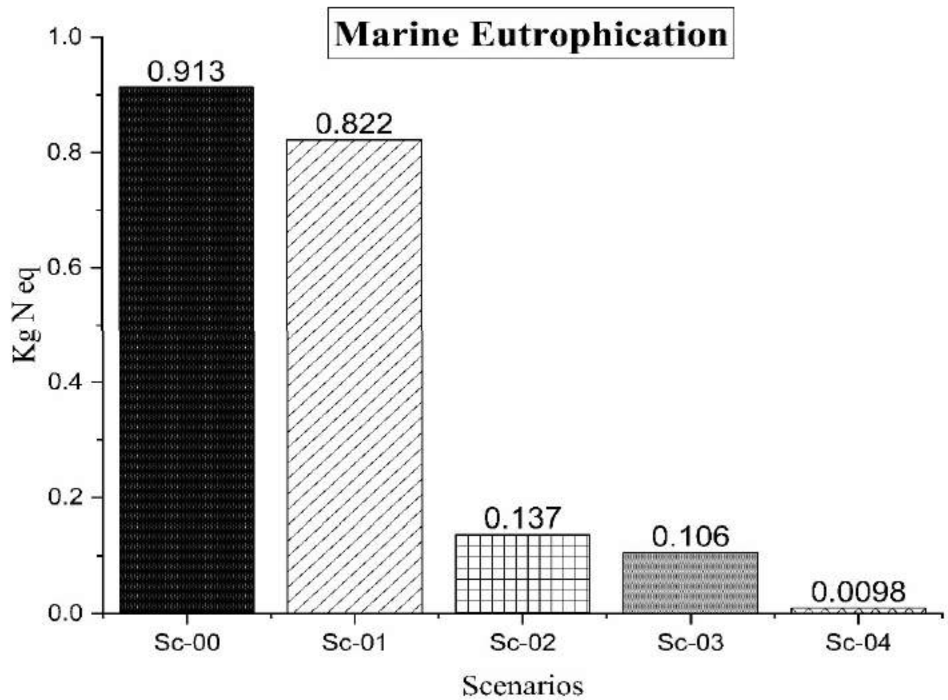


Figure 4.10 Marine Eutrophication

Marine eutrophication and hypoxia caused by excess nutrient availability is a growing environmental problem(Eldjorg et al., 2022). This trend is anticipated to persist, driven by the combined impacts of eutrophication—characterized by excessive nutrient availability, increased production of organic matter, and heightened oxygen demand in coastal systems and global warming, which raises respiratory oxygen demand while reducing oxygen solubility and ventilation in coastal waters (Vaquer-Sunyer and Duarte, 2008).The business-as-usual scenario, as shown in Figure 4.10 and Table 4.7, has the highest value of 0.913 kg N eq marine eutrophication for unsanitary landfills due to leachate production that contains local water sources. In contrast, scenario 01 has a relatively low impact due to sanitary landfill leachate management and treatment nevertheless, it still has a smaller chance of releasing nutrients than unsanitary landfills. Scenario 02 has a far lesser impact since composting, when done correctly, may keep most of the nutrients in organic matter. In Scenario 03, biogas has been generated because of organic waste decomposing. With an impact on the atmosphere of 0.106 kg N eq, this procedure sustainably retains nutrients and reduces their potential release into the environment. The lowest 0.0098 kg N eq potential for marine eutrophication is seen in Scenario 4. Together, composting and AD have a synergistic impact on keeping nutrients in the soil and delaying their discharge. The negligible fraction that ends up in landfills reduces the possibility of nutrient-rich leachate developing. In Serbia, there are over 3500 municipal solid waste landfills (MSWLF) that have been recognized as lacking adequate pollution control due to the underdeveloped solid waste management system (Karanac et al., 2015). Nearly all these landfills do not adhere to the EU Landfill Directive (1999/31/EC) and the EU Waste Framework Directive (2008/98/EC). These types of landfills pose significant risks to the environment (Krčmar et al., 2018; Ubavin et al., 2018), as they release a variety of pollutants into the landfill leachate landfill gas (which includes CO2, CH4, CO, H2S, and other gases) and heavy metals, xenobiotics, aromatic hydrocarbons, phenols, and other compounds (Jones-Lee and Lee, 1993; Kjeldsen et al., 2002; Mor et al., 2006; El-Salam and Abu-Zuid, 2015; Han et al., 2016; Youcai and Ziyang, 2017).

4.3.8 Mineral Resource Scarcity

Mineral resource scarcity assesses the environmental repercussions associated with the extraction and processing of minerals and metals integral to industrial processes. The issue is particularly pressing due to the scarcity of many minerals and the multifaceted impacts their extraction entails, encompassing both environmental and socioeconomic dimensions. The metric "kg Cu eq" quantifies these impacts by expressing them in terms of kilograms of copper equivalent. This standardized unit serves as a comparative benchmark, using copper as a reference mineral to gauge the environmental burden of extracting and utilizing other minerals.

The extraction of minerals contributes significantly to environmental degradation through habitat destruction, soil and water contamination, and greenhouse gas emissions. Furthermore, socioeconomic impacts include land use conflicts, displacement of communities, and economic dependency on fluctuating global commodity prices. Strategies to mitigate mineral resource scarcity often focus on recycling and efficient use of materials, substitution with more abundant or environmentally friendly alternatives, and improving extraction technologies to minimize environmental footprints. Scientific assessments employing life cycle assessment methodologies and material flow analysis play a crucial role in quantifying and addressing these impacts, guiding policies and practices toward sustainable mineral resource management.

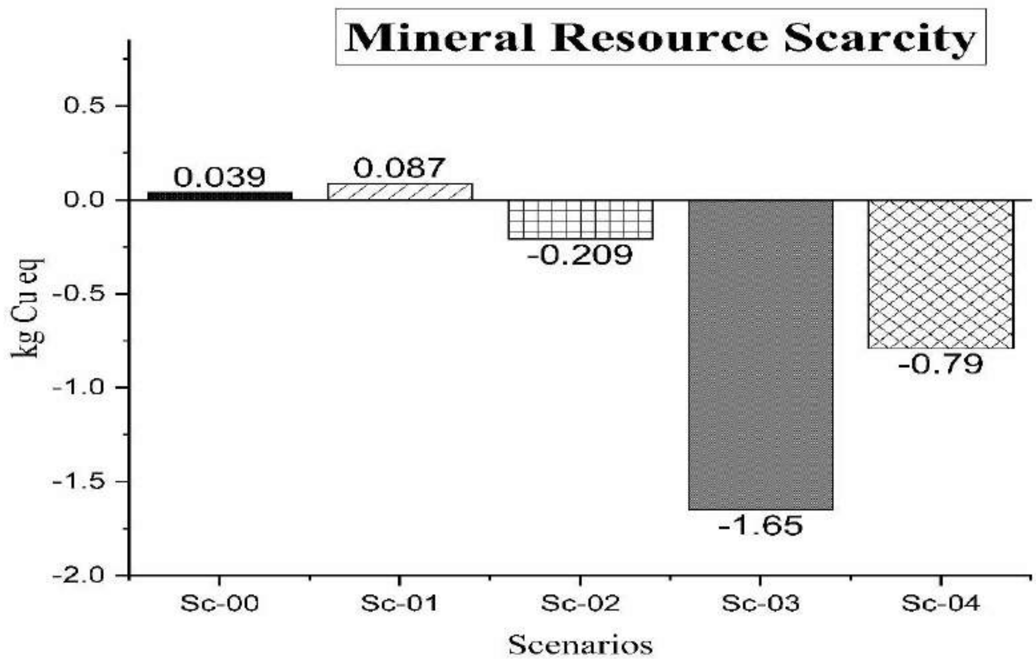


Figure 4.11 Mineral Resource Scarcity

Since sanitary landfills need more sophisticated infrastructure (liners, leachate collecting systems, and methane capture systems), which would demand more mineral resources than unclean landfills (Sc-00), Scenario 01 has the highest value of 0.087 kg cu eq as shown in Figure 4.11 and Table 4.7. Governments have been using landfills as quick and affordable ways to handle their domestic garbage. However, their use has an adverse effect on the environment because it requires a lot of land, emits gaseous pollutants (H2S, CH4), and produces a lot of leachates (Teng et al., 2021). One of the most difficult pollutants to treat is leachate, which is defined as water that percolates through landfill waste and is loaded with organic and mineral materials on a bacteriological and chemical level. The composition of leachate is primarily determined by the age of the landfill, the amount of precipitation, and the source of the landfill content (Gong et al., 2024, (Yuan et al., 2022). Scenario 02 most likely has a beneficial environmental impact since composting returns vital nutrients to the soil, reducing the need for synthetic fertilizer (which might require more mineral resources in its manufacturing). The scenario with the most significant environmental benefit is Scenario 3, which has a considerable -1.65 kg Cu eq impact. Anaerobic digestion emphasizes the efficiency of using methane as energy to replace conventional resource-intensive energy sources and replenish the soil with beneficial nutrients through digestate. The final scenario, Scenario 04, combines anaerobic digestion and composting to provide a middle-ground impact of -0.79 kg Cu eq that balances the advantages of both procedures. The study's findings showed that avoiding landfills and incorporating sustainable practices, such as composting and, notably, anaerobic digestion, may significantly lessen the demand for mineral resources, with anaerobic digestion showing the most significant environmental benefits.

4.3.9 Fossil Resource Scarcity

This metric counts for all direct and indirect fossil resource use during the lifespan of a process or product, including the use of coal, oil, and natural gas. A higher kg oil eq value in product, system, or resource assessments denotes greater dependence on these limited resources, indicating an increased probability of their depletion. This statistic is essential for comprehending the sustainability and viability of any given process or product, mainly as the world turns its attention to reducing its dependency on fossil fuels. The term "kg oil equivalent" (abbreviated kg oil eq) is used to show this impact.

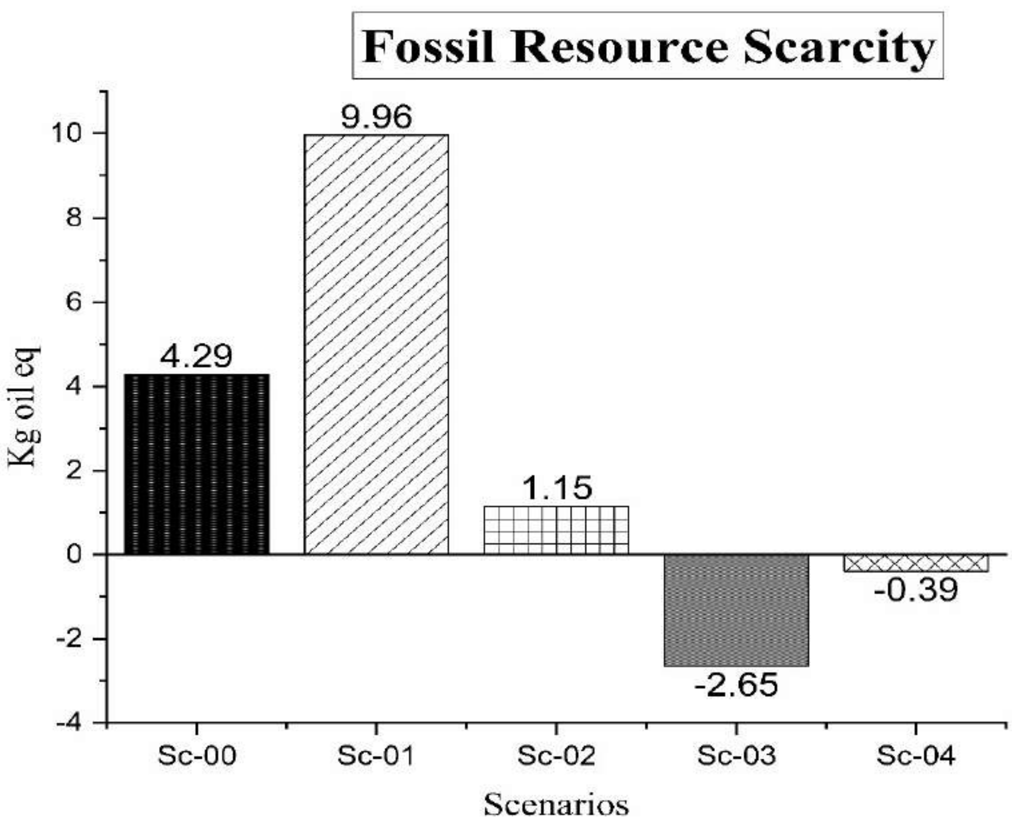


Figure 4.12 Fossil Resource Scarcity

According to Barro et al. (2018) and Ribeiro et al. (2018), biogas is mostly made of water, carbon dioxide (CO_2, 15–40 vol%), methane (CH_4; 35–65 vol%), a gas with significant greenhouse power, and 1%–15% of other gases, such as water vapor, H_2S, and NH_3. Biogas has multiple applications such as power generation, heating, and, after purification, the production of biomethane, which can be used as fuel for automobiles. GHG emissions are significantly reduced when biomethane is used in place of fossil fuels. Landfill biogas utilization presents an opportunity to mitigate greenhouse gas (GHG) emissions by substituting non-renewable energy sources, as highlighted by Barros et al. (2018). This approach reduces carbon dioxide emissions, thereby contributing to overall GHG reduction efforts, as supported by Ribeiro et al. (2018) and Mensah (2021). In Scenario 01, the energy consumption metric of 9.96 kg oil equivalent (kg oil eq) markedly surpasses the baseline value of 4.29 kg oil eq, indicating heightened reliance on fossil fuels in sanitary landfill operations. This increase is attributed to the substantial energy and resources required for waste handling, methane capture systems, and leachate management.

Conversely, Scenario 02 demonstrates a significant decrease of 1.149 kg oil eq due to composting, which facilitates the organic return of matter to soil with minimal energy input. This method contrasts with landfill operations by avoiding methane emissions and reducing energy-intensive waste management processes. Composting's lower energy demand and environmental benefits underscore its potential as a sustainable waste management strategy, aligning with goals to reduce fossil fuel dependence and mitigate GHG emissions. Scientific studies employing life cycle assessments and energy analysis methodologies are pivotal in quantifying these impacts and informing strategies for sustainable waste management practices.

In contrast, Scenario 03 uses the least fossil resources -2.65 kg of oil eq because AD not only keeps organic waste out of landfills but also collects methane (biogas) that can be converted into energy. This scenario may utilize less fossil fuel than it produces by switching to renewable biogas energy in place of fossil fuel-based energy. Due to the combination of AD and composting, which maximizes the environmental advantages of both processes, Scenario 04 has a value of -0.39 kg of oil equivalent. The net advantage in this case comes from the biogas created by the AD process, which offsets the use of fossil resources, and composting, which has a reduced resource impact.

4.3.10 Water consumption

This study investigates the effects of decreased freshwater availability as well as its broader ecological implications. A reduction in freshwater supplies causes reduced irrigation capacity, particularly Bluewater sources like lakes and aquifers, which increases the danger of malnutrition. This decrease in blue water is anticipated to affect green water resources, notably the moisture level of the soil, which will then influence plant and vegetative growth. The populations of fish in freshwater settings are also in danger due to this cascade impact. Water consumption in this context refers to the amount of freshwater used for various purposes that is taken from natural reservoirs but isn't replaced. The cubic meter (m^3), or a cube with a one-meter-long side, is the accepted unit for measuring water usage.

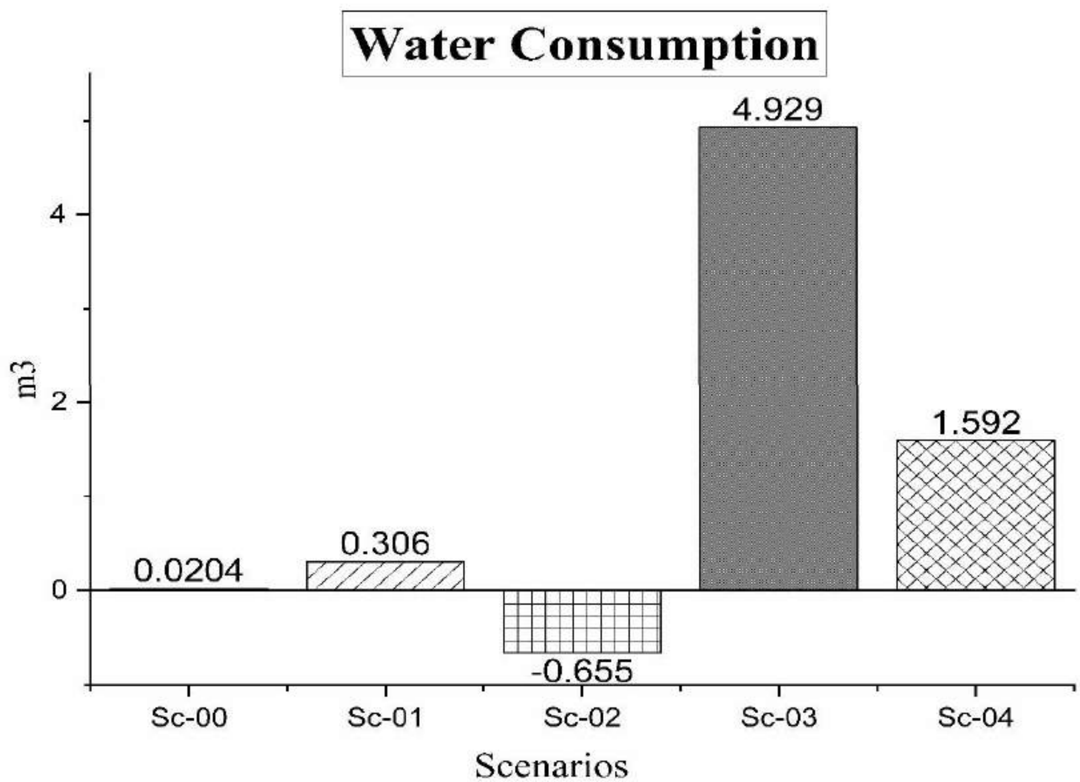


Figure 4.13 Water Consumption

The more sophisticated activities, such as leachate management (collection, treatment), and maybe methane management systems, can be attributed to the rise in water consumption, which is 0.306 m3 in sanitary landfills (Sc-01) compared to unsanitary landfills (0.0204 m^3) as demonstrated in

Figure 4.13 and Table 4.7. Leachate is a liquid that enters landfills through the rainfall layers and mixes with various hazardous pollutants produced by intricate hydrological, biogeochemical, and interaction processes. Large concentrations of high-level contaminants, including chemical oxygen demand (COD), sulfate, ammonia nitrogen, inorganic salts, and several kinds of heavy metals, are present in this soluble inorganic and organic molecule (Ma et al., 2022). The kind of waste being disposed of, the landfill's age, and the management techniques used can all have an impact on the wastewater's composition from landfills. Heavy metals, organic compounds, suspended particles, ammonia nitrogen, salts, pathogens, poisonous molecules that resemble humic materials, and micro/nanoplastics that are difficult to biodegrade are just a few of the dangerous contaminants that may be present (Gripa et al., 2023). Landfill wastewater's complexity and fluctuation are largely influenced by climate.

According to de Almeida et al. (2022), factors such as acid rain, pH variations, and temperature fluctuations influence the biodegradation rate of waste materials, impacting leachate generation and quality. Over time, the composition of landfill wastewater can change as different contaminants are released during waste decomposition. This variability poses challenges while creating efficient landfill leachate treatment plans, since the best course of action may change based on the particulars of the wastewater at any given time. The intricate nature of effluent from landfills emphasizes the need for strict management and oversight of landfill operations to reduce environmental effects.

While anaerobic digestion (AD) scenario 3 is increasingly recognized for its potential in conserving global water resources, its operation requires significant water usage (4.929 m^3 in the discussed scenario). This high-water demand supports microbial activity and maintains feedstock consistency but may necessitate additional water for digestate post-treatment. In water-scarce regions, this intensive water usage poses challenges and underscores the importance of assessing and managing water resources efficiently.

Scenario 02, involving composting, notably consumes the least water at 0.66 m3, as water is released as vapor during the composting process rather than being consumed. This highlights composting's advantage in water conservation compared to AD, emphasizing its potential as a sustainable waste management option in regions where water availability is limited. Scientific research is crucial in further understanding these impacts and developing strategies to optimize waste management practices while minimizing environmental and resource implications.

4.4 Endpoint Impact Assessment

The damage assessment is a thorough synthesis of endpoint metrics. The result of this complex procedure is a single score intended to comprehensively evaluate three key indicators: human welfare, ecological health, and resource sustainability. Table 4.8 thoroughly examines this Damage Appraisal as reported in the most current LCA research.

Table 4.8 Results of Endpoint Damage Assessment

Endpoint Damage categories	Unit	Sc-00 (UL)	Sc-01 (SL)	Sc-02 (COM+SL)	Sc-03 (AD+SL)	Sc-04 (COM+AD+SL)
Human Health	DALY	0.00388	0.00291	1.3E-3	4.56E-5	3.72E-4
Ecosystems	Species. yr	9.95E-6	4.0E-6	9.68E-7	4.73E-7	7.66E-7
Resources	USD2013	1.83	3.83	1.01	-15.2	-5.51

4.4.1 Human Health

Human health impacts are evaluated using Disability-Adjusted Life Years (DALYs) in endpoint damage assessment. DALYs quantify the burden of disease attributable to multiple contaminants and factors affecting human health. This metric integrates both mortality and morbidity impacts, providing a comprehensive measure of health outcomes affected by environmental exposures. Assessments using DALYs consider the severity and duration of health impairments caused by pollutants, facilitating comparisons across different contaminants and exposure scenarios.

The land application of composted municipal solid waste (C-MSW) serves to divert waste from landfills; however, it also represents a potential pathway for contaminants to enter the environment(Langdon et al., 2019). DALYs serve as a pivotal tool in environmental health risk assessment, aiding in prioritizing interventions and policies aimed at minimizing human health impacts from environmental exposures. By quantifying the years of healthy life lost due to diseases and disabilities associated with pollutants, DALYs inform decision-making processes to protect public health and promote sustainable development practices. Scientific advancements in epidemiology, toxicology, and exposure assessment continue to enhance the accuracy and applicability of DALYs in evaluating and managing environmental health risks worldwide.

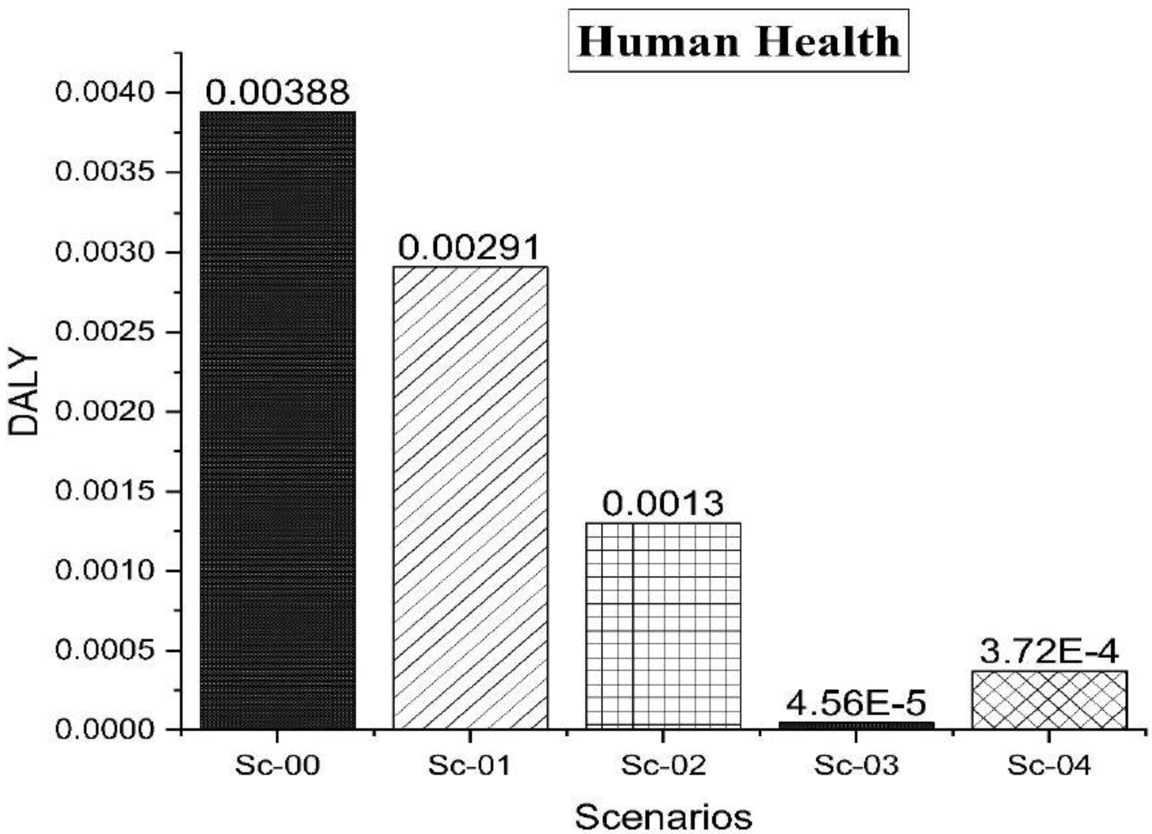


Figure 4.14 Human Health

Figure 4.14 and Table 4.8 show that Scenario 00's unsanitary landfill leads to the most significant health risk, with a DALY of 0.00388. According to Kjeldsen et al. (2002), landfill leachate is a highly contaminated liquid combination that contains microorganisms, organic debris, xenobiotics (such as pesticides), and inorganic chemicals (metals, chlorides, sulfates, etc.). Landfill leachate, if allowed to run wild, interacts with groundwater, surface water, and soil, lowering their quality and harming populated biodiversity (Kjeldsen et al., 2002; EPA, 1976; Alabaster and Lloyd, 1982; EPA, 1986; Öztürk et al., 2009). Consequently, it is crucial to collect and manage landfill leachate appropriately. Unsanitary landfills pose significant risks to human health through direct or indirect exposure to contaminated soil, air, and water sources, as documented by Tiembre et al. (2009).

Studies by multiple authors have linked unsanitary landfill conditions to various adverse health effects, including increased incidence of cancer (Jarup et al., 2002; Porta et al., 2009; Mattiello et al., 2013), adverse birth outcomes (Dolk et al., 1998; Elliott et al., 2009), respiratory diseases, and issues related to excess noise (Aatamila et al., 2011; Heaney et al., 2011; De Feo et al., 2013).

Scenario 01, involving a sanitary landfill, represents a modest improvement with a Disability-Adjusted Life Year (DALY) burden of 0.00291, attributed to reduced emissions compared to unsanitary conditions. Scenario 02, integrating landfill operations with composting, significantly reduces health risks with a DALY of 0.00013, underscoring the effectiveness of composting in mitigating environmental and health impacts. In Scenario 03, which employs anaerobic digestion (AD), the DALY further decreases to 0.0000456, highlighting AD's efficacy in emission reduction. However, the hybrid approach in Scenario 04 surprisingly reports a higher DALY of 0.00372, suggesting potential inefficiencies or compounded health risks associated with combining composting and AD.

These findings emphasize the critical importance of waste management strategies in mitigating health impacts associated with landfill operations. Scientific research continues to refine understanding of these impacts, informing policies and practices aimed at reducing environmental and health risks while promoting sustainable waste management solutions.

4.4.2 Ecosystem

Ecosystem endpoint damage assessment quantifies impacts using the metric "species.yr," which measures the potential loss of species-years due to environmental pressures in each area. This metric provides a comparative measure where lower (or more negative) values indicate less severe ecosystem impacts. It assesses the cumulative effects of environmental stressors on biodiversity, reflecting the combined influence of habitat degradation, pollution, climate change, and other factors on species viability and ecosystem resilience.

"Species.yr" is widely utilized in ecological studies to evaluate the long-term impacts of human activities on biodiversity and ecosystem health. By estimating the years of species lost or impacted by adverse environmental conditions, this metric aids in prioritizing conservation efforts and guiding sustainable development practices. Scientific methodologies, including habitat modeling, population dynamics, and species distribution analysis, contribute to the accuracy and relevance of "species.yr" assessments.

Understanding and mitigating ecosystem endpoint damage are crucial for biodiversity conservation and ecosystem services. Effective management strategies, informed by robust scientific assessments, are essential to minimize anthropogenic impacts and safeguard biodiversity for future generations. Continued research and monitoring are imperative to enhance our understanding of ecosystem dynamics and inform evidence-based conservation policies globally.

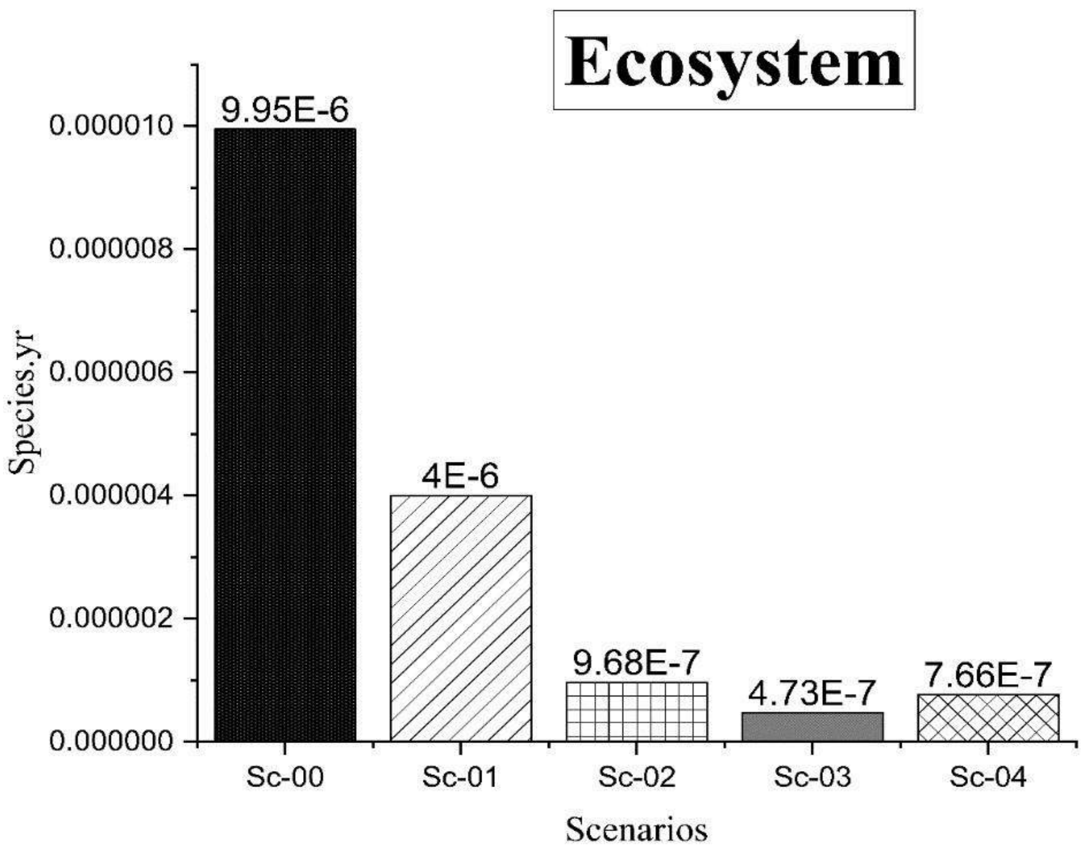


Figure 4.15 Ecosystem

Rapid population growth and heightened resource utilization have escalated organic waste emissions, underscoring the urgent need for sustainable waste management in densely populated areas. Biological treatment stands out as an effective method for reducing organic waste volumes while also generating energy(Odlare et al., 2011).Our baseline scenario, as shown in Figure 4.15 and Table 4.8, includes the environmental dangers of methane and possible leachate contamination, with the most significant negative impact at 9.95E-6 species. yr. In Scenario 01, switching to sanitary landfilling reduced this impact by half, illustrating the benefits of enhanced management. However, the ensuing scenarios' innovative methods were what demonstrated environmental stewardship. Anaerobic digestion in Scenario 03, with a measly 4.73E-7 species. yrs., stood out as the height of sustainable waste management, whereas composting in Scenario 02 lowered the effect to 9.68E-7 species. yr. In Scenario 04, the hybrid method produced a balanced impact of 7.66E-7 species.yr, showing the effectiveness of mixed approaches.

In a Life Cycle Assessment (LCA) of organic wastes, resource analysis focuses on evaluating the inputs and outputs throughout the waste management process, from collection to disposal. This includes the consumption of raw materials, energy, and water, as well as the potential recovery of nutrients and energy through methods like composting and anaerobic digestion. By assessing these factors, LCA helps identify sustainable waste management practices that reduce resource depletion and environmental impact, supporting a circular economy where organic waste is effectively transformed into valuable resources. Landfills generate two primary waste streams: leachate, a highly concentrated liquid containing various pollutants, and landfill gas, predominantly methane, a potent greenhouse gas contributing to global warming. Soil-dwelling microbes play a crucial role in decomposing organic materials present in discarded waste items. According to Aich and Ghosh (2016), achieving sustainability in municipal solid waste management (MSWM) systems necessitates integrated treatment strategies beyond technical solutions alone.

Liquid leachate poses significant environmental risks when it infiltrates soil and water systems, particularly during rainfall events, as noted by Costa et al. (2019). Leachate from landfills is characterized by a complex mixture of organic and inorganic pollutants, suspended particles, heavy metals, nitrogenous compounds, organic acids, humic substances, xenobiotic compounds (such as pesticides and phenols), and plastics. The composition of leachate varies depending on the types of solid waste deposited in landfills.

The presence of these contaminants in leachate underscores the potential ecological hazards associated with improper landfill management. Effective containment and treatment strategies are essential to mitigate the environmental impacts of leachate discharge into surrounding ecosystems. Scientific research continues to advance understanding of leachate composition and behavior, guiding efforts to develop sustainable waste management practices and minimize environmental contamination from landfill operations.

4.3.3 Resources

The unit "USD2013" serves as a standardized measure for expressing financial or economic statistics in terms of the value of the United States dollar as of the year 2013. This approach allows for adjustments that account for inflation and other long-term economic changes over time. By anchoring economic data to a specific reference year, USD2013 facilitates comparisons across different time periods and regions, enabling researchers, policymakers, and analysts to assess and interpret financial trends and economic indicators with greater accuracy and consistency.

The use of USD2013 is particularly valuable in economic analysis, where it ensures that data are comparable and relevant despite fluctuations in currency values and purchasing power over the years. This standardization method is applied in various fields, including cost-benefit analysis, economic forecasting, and historical economic studies, providing a reliable framework for evaluating economic performance and policy impacts across diverse contexts.

Moreover, USD2013 allows for the assessment of real economic changes by filtering out the effects of nominal value fluctuations caused by inflation or currency devaluation. This approach enhances the reliability of economic assessments and supports informed decision-making by policymakers and stakeholders seeking to understand and address economic challenges and opportunities effectively. Continued research and application of USD2013 methodology contribute to advancing economic analysis and policy formulation in an increasingly dynamic global economy.

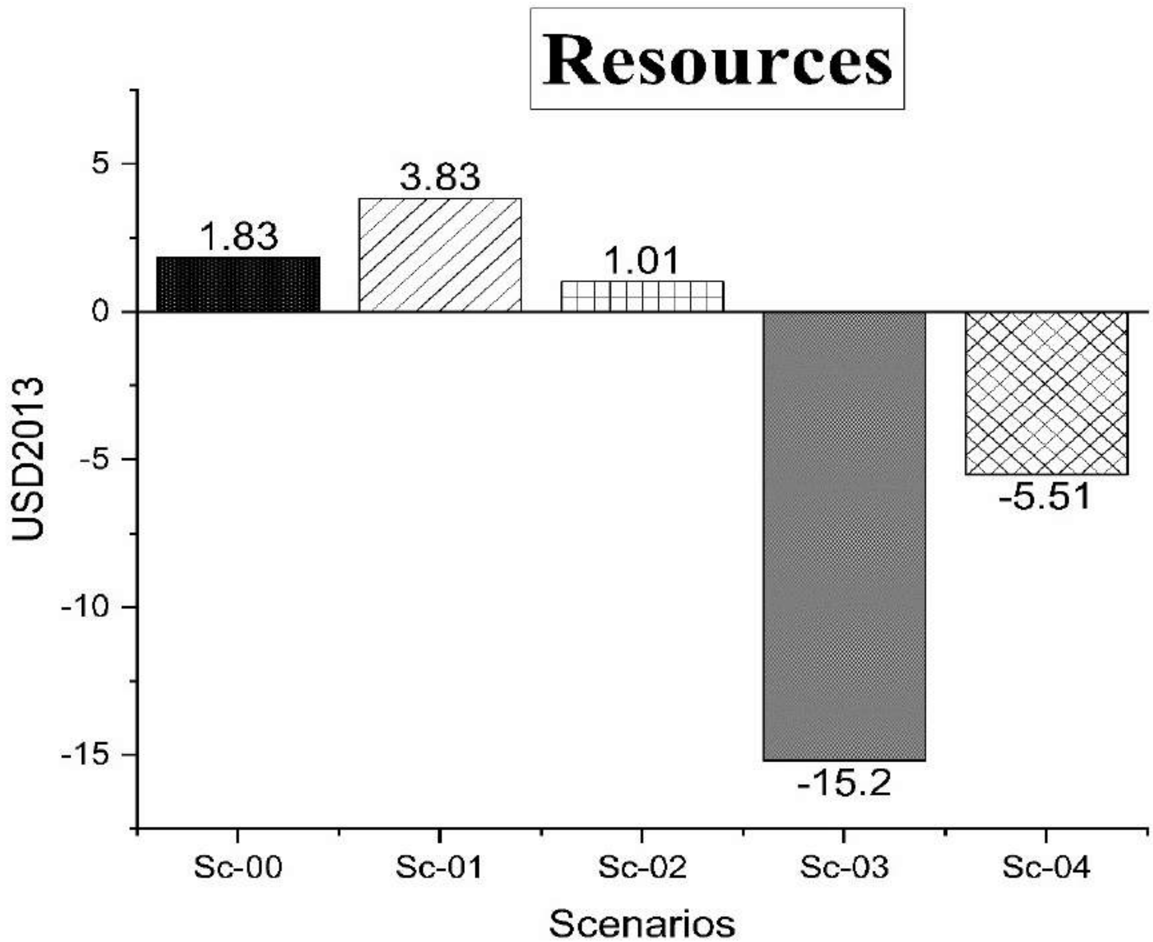


Figure 4.16 Resources.

Scenario 00, which uses unsanitary landfills, resulted in an environmental cost of $1.83 in 2013, as shown in Figure 4.16 and Table 4.8. In Scenario 01, switching to a sanitary landfill raises the price to $3.83 USD2013, raising the specter of increased resources needed despite improved management. In a Life Cycle Assessment (LCA) of excavation and mining, resource analysis entails evaluating the inputs and outputs from extraction through to waste disposal. This encompasses the assessment of energy, water, and material usage, alongside the environmental impacts such as land disturbance and habitat loss. The LCA provides insights into sustainable practices by examining the environmental consequences of resource extraction, the effectiveness of material recovery, and opportunities for minimizing waste and emissions, with the ultimate goal of reducing resource consumption and environmental harm. The concept of excavating and mining landfill sites has emerged as a strategy to treat them as temporary storage until technologies for waste valorization become feasible (Bosmans et al., 2013; Van Passel et al., 2013; Jones et al., 2012; Savage et al., 1993; Hogland et al., 2004). Including composting in waste management practices, as demonstrated in Scenario 02, significantly reduces the economic burden to $1.01 USD2013, underscoring composting's environmental benefits and cost-effectiveness.

Scenario 03 presents a compelling economic advantage of -15.2 USD2013 alongside reduced environmental impacts, highlighting the efficacy of integrated waste management strategies. Conversely, the hybrid approach of Scenario 04, combining anaerobic digestion and composting, yields a lower economic benefit of -5.51 USD2013, indicating potential challenges in integrating these processes effectively.

These findings underscore the importance of adopting sustainable waste management practices that align with circular economy principles to enhance resource recovery, reduce environmental footprints, and optimize economic outcomes. Continued research and innovation in waste valorization technologies are essential for advancing these goals and addressing the global challenge of managing plastic waste effectively.

4.5 Sensitivity Analysis

Sensitivity analysis of the organic waste treatment LCA (Life Cycle Assessment) results at Islamabad University was carried out to determine how different parameters affected the different damage categories. Tornado charts were used in the assessment to show sensitivities under a deviation of ±10 % from the mean values of essential parameters, holding all other variables constant. The average environmental impacts for each damage category are shown in Figure 30 by the central vertical line. Any departure from this line showed the impact of changing the parameter values by 10%.

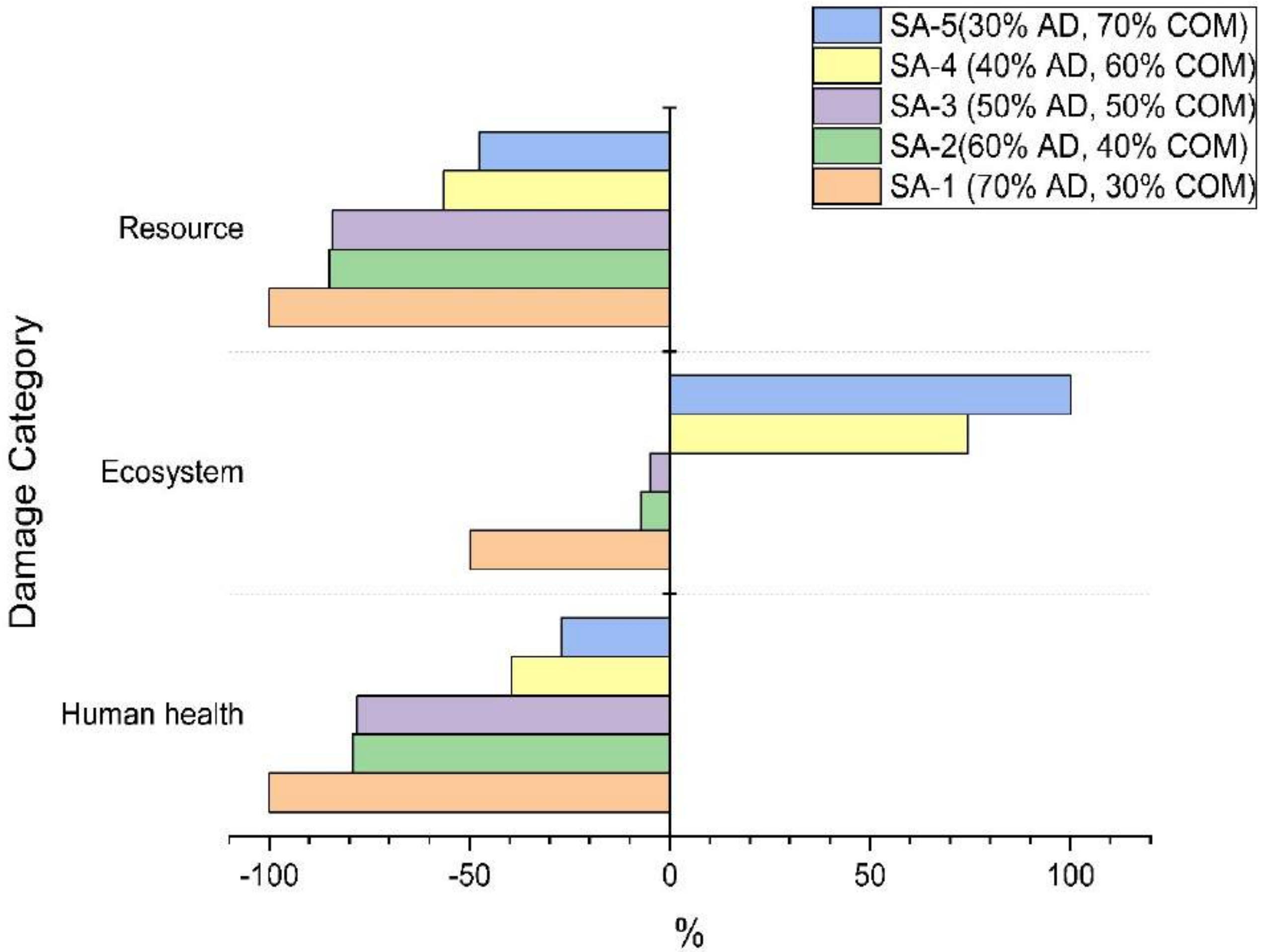


Figure 4.17 Sensitivity Analysis Results

Table 4.9 Sensitivity Analysis Results

Damage Category	**Units**	**SA-1**	**SA-2**	**SA-3**	**SA-4**	**SA-5**
Human health	DALY	-0.00032	-0.000251	-0.000247	-0.000119	-7.77E-5
Ecosystem	Species.yr	-4.36E-8	1.87E-8	2.23E-8	1.38E-7	1.76E-7
Resource	USD2013	12.9	-10.8	-10.7	-6.91	-5.69

It is evident, based on the graph's damage assessment across three categories—human health, ecosystem, and resources as shown in Table 4.9 and Figure 4.17 that organic waste that has received a more significant percentage of AD treatment tends to be more productive. In particular, the SA-1, which uses 70% AD and 30% composting, showcases the least detrimental effects on resources and human health as we get compost and biogas as an output that can be further utilized as renewable energy. This implies that AD is potentially effective at treating and comprising possible pollutants while being resource efficient. However, it is concluded that the environment is only moderately impacted by any of the extreme AD ratios.

4.5.1 Discussions

The results with suggestions of the Life Cycle Assessment (LCA) on methods for managing organic waste. To fully assess the environmental impacts of organic waste management, the analysis covered all phases of the process, from collection to ultimate disposal or recycling. The LCA results highlighted important environmental consequences of various approaches to managing organic waste. For example, EPA (2020) showed that, when compared to landfilling, composting and anaerobic digestion provide significant benefits for lowering greenhouse gas emissions. This is consistent with other research highlighting the function of managing organic waste in reducing overall environmental footprint and mitigating climate change (Parfitt et al., 2010). One important element that came out of the LCA findings was resource efficiency. Composting is one strategy that lowers methane emissions while also producing nutrient-rich compost that can improve soil health and agricultural output (Finkbeiner et al., 2010). Anaerobic digestion, on the other hand, produces biogas, a renewable energy source, supporting the circular economy concept by turning waste into useful resources (UNEP, 2015). It was also considered whether various organic waste treatment technologies might be used while keeping in mind both economic viability and technological improvements. Even if certain technologies have larger upfront costs, they frequently have longer-term positive effects on the environment and the economy than negative effects (Garcia-Gusano et al., 2018). This emphasizes how crucial it is to incorporate environmental evaluations and economic analysis in order to guarantee sustainable waste management techniques. Policies and regulations that are effective are essential in determining how organic waste is managed. Policymakers can gain significant insights from the Life Cycle Assessment (LCA) findings, which highlight the need for supportive policies that encourage sustainable waste management methods and prohibit the disposal of untreated trash in landfills (DEFRA, 2019). Furthermore, global frameworks for developing sustainable waste management techniques are provided by international agreements like the Sustainable Development Goals (SDGs) (UN, 2015). Notwithstanding its merits, this research admits significant drawbacks, such as imprecise data and the requirement for more thorough life cycle assessments including wider geographic regions and waste categories (Kumar et al., 2021). Subsequent studies should concentrate on improving LCA techniques, strengthening the integration of social and economic aspects, and investigating novel technologies for the value-adding of organic waste. The life cycle assessment (LCA) conducted on organic waste management practices within university settings provides critical insights into the environmental impacts associated with these operations. Universities, as centers of learning and research, generate significant amounts of organic waste, primarily from dining facilities and campus events. This waste often ends up in landfill sites where it contributes to methane emissions—a potent greenhouse gas. However, the implementation of alternative waste management strategies such as composting and anaerobic digestion offers promising avenues for reducing environmental impacts. Composting, for instance, facilitates the conversion of organic waste into nutrient-rich soil amendments, thereby mitigating greenhouse gas emissions associated with landfilling (Smith et al., 2020). The comparative analysis of waste management strategies reveals distinct advantages of composting and anaerobic digestion over landfilling. These methods not only reduce methane emissions but also potentially recover valuable nutrients from organic waste, contributing to circular economy principles (Jones & Green, 2019). Moreover, the environmental benefits of these strategies extend beyond greenhouse gas emissions reduction to include conservation of natural resources and support for sustainable agricultural practices. These findings underscore the importance of adopting holistic waste management approaches that consider the entire life cycle of organic waste—from generation to disposal or conversion into valuable products. The influence of local context and infrastructure emerges as a crucial factor in determining the effectiveness of waste management strategies within university environments. Regions with well-established composting facilities and supportive policies tend to exhibit lower environmental burdens associated with organic waste management. In contrast, areas lacking such infrastructure may struggle to achieve similar environmental benefits. Therefore, policies and investments aimed at enhancing local waste management infrastructure and promoting sustainable practices are essential for achieving meaningful reductions in environmental impacts across university campuses.

Chapter 05: Conclusions and Recommendations

This chapter summarizes the study's principal conclusions and makes actionable recommendations based on them. It tackles the study's objectives and answers the opening question. The analysis's essential findings and how they relate to the larger subject area or context are emphasized.

5.1 Conclusion

In conclusion, the study underscores the critical importance of adopting sustainable waste management practices, particularly in the context of organic waste. The findings reveal that traditional methods such as sanitary and unsanitary landfilling pose significant environmental risks, including methane emissions and water pollution. On the contrary, composting, and anaerobic digestion emerge as promising alternatives, with anaerobic digestion showing the greatest potential for mitigating global warming. While anaerobic digestion generates particulate matter during combustion, its overall environmental benefits outweigh this drawback, especially when considering its ability to transform methane into biogas. Moreover, the study emphasizes the need to consider long-term emissions and specific waste management activities when assessing environmental impacts. Anaerobic digestion is highlighted as the most advantageous option for managing organic waste, supported by evidence from previous research studies. These findings reinforce the importance of transitioning towards more sustainable waste management practices to minimize environmental harm and mitigate climate change. Overall, the study provides valuable insights into the environmental implications of different waste management scenarios and underscores the urgent need for policymakers and stakeholders to prioritize sustainable waste management strategies. By implementing practices like anaerobic digestion and composting, we can not only reduce greenhouse gas emissions but also protect ecosystems and promote resource efficiency.

5.2 Recommendation

Implementing these recommendations can considerably improve the sustainability and environmental performance of organic waste management systems.

- Priorities anaerobic digestion for organic waste treatment, as AD Absorb methane and turns it into biogas, which reduces methane emissions while providing renewable energy.

- Scaling up composting facilities can drastically reduce the amount of organic waste imposed on landfills, thus contributing significantly to environmental initiatives for sustainability.
- In scenarios necessitating waste disposal, improving the management of both sanitary and unsanitary landfills is essential. This includes building rigorous emission control systems to reduce methane emissions and effectively manage leachate to prevent water pollution.
- This research emphasizes the importance of conducting comprehensive life cycle assessments (LCAs) when analyzing organic waste management scenarios. It emphasizes the importance of improving LCA databases with current and region-specific data to facilitate decision-making and ensure accurate environmental impact assessments.
- Introducing sustainable organic waste management strategies such as composting and anaerobic digestion through public awareness and education will boost community engagement and implementation feasibility.

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