

UNIVERSITY OF BAHRAIN

College of Science



Environment and
Sustainable Development
Program

A Study of Municipal Solid Waste Management in the Kingdom of Bahrain: Application of Life-Cycle Optimization and Sustainability

A Thesis Submitted in Partial Fulfilment of the Requirements for the
Doctor of Philosophy Degree in Environment and Sustainable
Development

Submitted by

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Supervised by

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University of Bahrain

Kingdom of Bahrain

June 2025

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Abstract

Municipal solid waste management (MSWM) is vital for sustainable development and achieving the SDGs. Bahrain faces increasing pressure, requiring evidence-based strategies to reduce environmental harm. With global waste rising from 2.1 billion tons in 2023 to 3.8 billion by 2050, and costs surpassing US\$360 billion, urgent action is essential.

This study proposes a comprehensive model for sustainable MSWM in Bahrain. It evaluates the current system, assesses SDG alignment, and analyzes potential improvements through environmental, social, and economic lenses. Life Cycle Assessment (LCA) using OpenLCA was applied to seven treatment scenarios, measuring six environmental impact categories. Life Cycle Costing (LCC) was used to assess economic viability. Public surveys and expert consultations were also conducted to integrate stakeholder perspectives.

The study presents the SELECT model—an acronym for Social, Environmental, Legislation, Energy, Cost-effectiveness, and Technology—as a framework for guiding sustainable waste decisions. Composting emerged as the most sustainable treatment scenario, followed by recycling and gasification. Bahrain demonstrated strong performance in SDGs 11, 12, and 17; average performance in 3, 8, 9, 13, and 15; and minimal progress in Goal 14.

Practical implications include guiding MSWM reforms, reducing landfill pressure, mitigating climate impacts, and supporting national strategies. The research also provides comparative insights between current and improved systems concerning SDGs outcomes. Limitations include focusing on the geographical context of Bahrain and excluding hazardous, medical, and informal waste due to their unique characteristics. Local data were used whenever possible; otherwise, international databases such as Ecoinvent were applied. This study contributes to scientific and policy dialogues by supporting decision-making, infrastructure planning, and sustainability monitoring.

DEDICATION

My sincere thanks to all my loved ones, my daughters Maha and Zainab, and my friends, who put up with my preoccupation with preparing my doctoral thesis. My special thanks to my parents for their prayers and long wait for my graduation, to the soul of my father who passed away without seeing me graduate, and to all my friends, family members, and the people of my village for my absence from social work with them. I dedicate this achievement to all my teachers, friends, colleagues, and everyone who waited for this moment.

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LIST OF ACRONYMS

In this section, the research identifies the main terms that appear in the study, as well as the definitions of those terms. These terms are arranged alphabetically for easy searching.

AI	Artificial Intelligence
CML	Institute of Environmental Sciences, Leiden University, Netherlands
EC	European Commission
ELCD	European reference Life Cycle Database
EPLCA	European Platform on LCA
EU	European Union
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IES	Institute for Environment and Sustainability
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
ISWM	Integrated Solid Waste Management
IWM	Integrated Waste Management
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
MADM	Multi-Attribute Decision-Making Model

MFA	Material Flow Analysis
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
OECD	Organization for Economic Cooperation and Development
SETAC	Society of Environmental Toxicology and Chemistry
UUID	Universally Unique Identifiers
VNR1	First Voluntary National Review
VNR2	Second Voluntary National Review

Chapter 1. Introduction to the study

1. Introduction

Sustainability of waste management has become a global requirement and the pursuit of it is not in vain. It is considered a pivotal issue that contributes to environmental safety, human health, and the preservation of natural resources, which is what sustainable development calls for in its goals (Malav et al., 2020). Food waste is an ethically unacceptable behavior, as at a time when more than 820 million people in the world suffer from hunger, there is food waste without realizing their suffering and need for this waste food (WHO, 2019). It is also a negative source of environmental impacts such as GHG that affect the climate. Moreover, it is an important contributor to GWP once it is dumped in landfills, in landfills it decomposes and generates methane gas 25 times stronger than carbon dioxide (CO₂) (FAO, 2013; Zhang et al., 2019). Disposing of food waste in landfills causes GHG emissions and soil pollution (Shahzad et al., 2017).

Food waste is considered an economic loss, as money is spent on food while it is thrown away. In 2018, the annual per capita food expenditure in the GCC countries ranged around US\$1951.9 (13.71% of total expenditure) and US\$1674.1 (13.24%) in Bahrain (El Bilali & Ben Hassen, 2020). Abdallah et al. (2018) also found that there is financial viability in converting waste to energy using several methods, including anaerobic digestion and incineration. Considering the utilization of waste in waste-to-energy, especially the development of renewable energy, contributes to solving MSW problems, encourages new business development, creates jobs, and improves the environment and public health.

This thesis focuses on proposing a conceptual model for sustainable Municipal Solid Waste Management (MSWM) and utilization that is suitable

for Bahrain's environment and capabilities. To determine the best way to reduce, reuse, and recycle MSW, waste management is a priority for the Sustainable Development Goals (SDGs), and a sustainable society is efficient in using resources and achieves a sustainable economy. To achieve this, MSWM must be improved through recycling materials, recovering energy, closing key material loops, and preserving the environment by reducing toxic materials and gas emissions. The SDGs emphasize responsible production and consumption, which emphasizes improving MSWM practices in the required manner, and the world is now moving towards a circular economy, which is commonly referred to as industrial ecology, green economy, and smart economy. Waste management studies have gained global attention because they represent a global problem. With the increasing global population and the successive growing urban development, waste generation is increasing and its negative impacts on the world are increasing, posing a challenge to the world from environmental, economic, and social aspects (Malav et al., 2020).

1.1.1 Reasons for increasing food waste.

One of the causes of waste generation is food waste, and this occurs especially in developing countries for several reasons, including weak culture, lack of awareness, customs, and traditions (Baig et al., 2019; El Bilali & Ben Hassen, 2020). Among the factors that contribute to the increase in food waste in the GCC countries is preparing food for social occasions such as births and deaths in large quantities that exceed the number of guests, and the Gulf people's pride in their social status and wealth (Abiad & Meho, 2018). To achieve the success of sustainable waste management, the research proposes to explore the factors that help it. The criteria that make MSWM environmentally friendly will be investigated. The management tools, administrative

alternatives, and opportunities that enable decision-makers and executives to achieve the desired goal will also be discovered.

1.1.2 The importance of dealing with waste innovatively

With the increasing amounts of waste around the world, it is important to think of innovative ways to deal with waste to avoid environmental and societal risks (Naveenkumar et al., 2023). Countries spend huge amounts of money on waste management and treatment, which leads to economic losses and multiple impacts on the environment. Here comes the importance of having advanced technology to avoid these losses and find sustainable technology that reduces environmental impacts. It is possible to consider advanced methods for the path of MSW from source to landfill in the field of collection, transportation, and treatment. Technology should contribute to the sustainable management strategy of MSW for environmental protection and economic stability. The development of smart MSWM systems has an effective impact on environmental conservation and resource utilization.

1.1.3 Adopting an appropriate waste management model

With the annual increase in waste in the world, the risks to ecosystems are increasing, which calls for the need to develop indicators to monitor waste management performance to mitigate negative impacts and preserve and sustain the environment (UNEP, 2017; European Commission, 2005). Hence, the importance of developing an administrative strategy to deal with waste in a manner that suits the country itself and studying its options, capabilities, and economic situation. The method of studying waste management and its impact on the environment can be carried out to make it sustainable through life cycle assessment (LCA) and exploring the factors that lead to the sustainability of

MSWM. This research details the status of MSW in Bahrain and then conducts a literature review leading to the development waste management model. Then evaluates the environmental, economic, and social aspects of MSWM, explores sustainability factors, and then organizes and draws a model for sustainable MSWM. The importance and role of LCA in the evaluation and design of sustainable MSWM systems lies in its comprehensive nature from start to finish, from collection, transportation, sorting, and treatment to final disposal, which effectively assesses energy use, emissions, and resource depletion (Dangi, M. et al., 2023).

1.1.4 Global Waste Management in 2024

The UNEP (2024) report provides an update on global waste generation, waste costs, and management since 2018. The report forecasts MSW generation to grow from 2.1 billion tons in 2023 to 3.8 billion tons by 2050. The direct global cost of waste management in 2020 was estimated at approximately US\$252 billion. The cost rises to US\$361 billion when considering the hidden costs of pollution, poor health, and climate change caused by poor waste disposal practices. The annual cost could double to US\$640.3 billion by 2050 if urgent action is not taken on waste management. When measures are taken to prevent and manage waste sustainably, it could reduce net annual costs by 2050 to US\$270.2 billion. If a circular economy is adopted, where the necessary measures are taken to segregate waste, adopt waste avoidance, sustainable practices, and dependable waste management, the cost could reach US\$108.5 billion.

1.1.5 Pioneering LCA-Based MSWM Research for Sustainable Development in Bahrain

This research illustrates the importance of studying MSWM and linking it to sustainable development, with the assessment of the relevant SDGs. It also evaluates the implementation of these goals in Bahraini society. It logically evaluates the reality of MSWM using the LCA method. This study is the first in Bahrain to use this method, which researchers recommend using. The research proposes a conceptual model for the sustainability of MSWM and tests each of the proposed elements. The research tests seven scenarios, studies six environmental categories for each, and evaluates them to determine the best one. The research uses the LCA method and the Ecoinvent database, which compensates for the lack of data that was not available for the research. The method used is characterized by its development and advancement, as previous research has shown, and is recommended by the European Commission (EC) (Mali & Patil, 2016). This research will clarify the important limits for decision-makers in Bahrain to focus on the most important elements for the sustainability of waste management (Al Sabbagh, 2012). The research demonstrates the environmental, social, and economic importance of choosing the optimal scenario and the criteria, tools, and administrative alternatives that help decision-makers for sustainable decisions. The research results provide a step towards applying the OpenLCA software in the field of waste management. Linking the research gap to the research objectives and questions.

1.2 Research Problem

The amount of waste is increasing daily, the population is growing steadily, urbanization is also growing, and the predominant way of disposing of waste is by dumping it in a landfill. Based on the enormous volumes of waste produced and the space used daily, Khalil (2017) claims that the Askar landfill has reached the end of its useful life since 2016. In addition to the harm this garbage disposal approach causes to the environment. This reflects the lack of a sustainable strategy for dealing with MSWM that is suitable for the long term. More than that, recent studies have proven that waste should be considered wealth, and benefiting from it achieves the SDGs (Bernstad, 2010). Therefore, there is a need for a method to manage MSW to reduce landfills and pressure on landfills, as well as to make use of recyclable waste economically.

With the increase in waste and, consequently, increasing environmental harms on the earth and human health, and many problems that follow, it is necessary to study and analyze the methods used for waste management to solve this dilemma. The world is also moving today towards achieving SDGs for the safety of the environment and preservation of the natural resources of the earth for future generations, and the health of humans and living creatures on this earth. The problem of waste has become a dilemma that stands in the way of achieving the SDGs.

The UN in 2017 considered waste management as a “fundamental human right” for society and the economy (Abas et al., 2022). Despite all these quantities that impact the environment, this MSW is not recycled. Landfills emit powerful GHG estimated at 40 to 50 percent methane (CH₄), leading to

a potential GWP 23 times higher than carbon dioxide (UNEP, 2017). MSWM is an essential issue in the world, and it is getting more complicated due to the increase in population in their daily needs. Most of the developing countries are suffering from this problem.

As previous statistics have shown the highest percentage of the waste collected is biodegradable waste (Andraskar et al., 2023). The focal point is on how to treat this type of waste effectively. Biodegradable waste can be treated using composting by anaerobic digestion, which can be done through LCA (Theekshana & Ariyaratna, 2022). The LCA application identifies and mitigates damage, identifies strategies to reduce the amount of waste that puts pressure on landfills, and helps determine the most appropriate treatment method for the Kingdom of Bahrain.

1.2.1 Waste management

The situation is worrying in rural areas, especially in the context of developing and underdeveloped countries, where there is a dearth of scientific waste management strategies. Solid waste generation has its own high costs and global footprint. SWM costs US\$205.4 per ton on average globally, with a projected five-fold increase by 2030 (Hoornweg & Bhada-Tata, 2018). There is a close association between waste generation and air, soil, and water pollution (Brunner, 2013). The leachate generated from local solid waste discharges minerals and toxic components that pollute surface water, groundwater, and soil, and MSW in landfills causes global methane emissions. Solid waste also contributes about 800 tons of carbon dioxide per year to the atmosphere. Also, the generation of solid waste causes the spread of many health risks and major diseases to the population, such as dermatitis, malaria,

bronchitis, digestive disorders, and asthma for those who live near landfills (De & Debnath, 2016).

1.2.2 Waste Management in the GCC Countries

El Bilali and Ben Hassen (2020) believe that food waste has become a very important challenge in the GCC countries, leading to an increase in waste. The GCC-STAT (2021) shows that the amount of food wasted amounted to about 131.8 million tons in 2018 in the GCC countries. The per capita share in the countries of the GCC ranged between 0.96-1.91 kg/day of the amount of household waste collected during 2016 (GCC-STAT, 2021). While it is in 2022 reached between 1.5-1.8 (GCC-STAT, 2024).

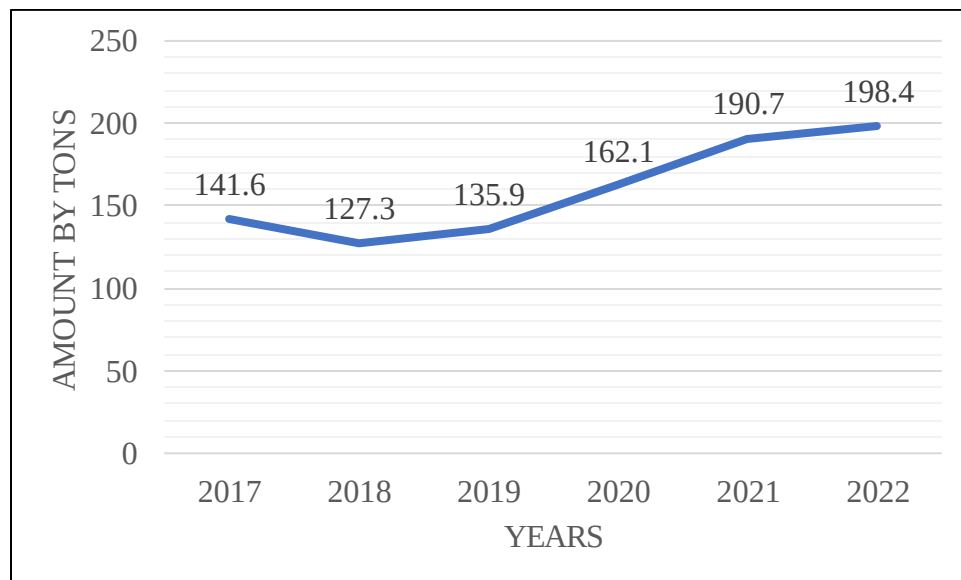


Figure 1.1: Total Non-Hazardous Waste Collected in GCC Countries for the Period 2017-2022.

Source: (GCC-STAT, 2024)

The statistics indicate that there has been a steady increase in the number of landfills in the GCC countries from 2015 to 2018. If the situation continues, more landfills will be needed, so it is necessary to study this challenge and seek sustainable solutions. The total non-hazardous waste collected in the GCC countries in 2022 amounted to about 198.4 million tons, with an average of 40.1% during the period 2017 and 2022, as shown in Figure 1.1.

For example, Saudi Arabia is moving toward a circular economy. It launched the National Waste Management Strategy (2021) to recycle 81% of waste by 2035 (Research and Markets, May 2025). The UAE also aims to achieve zero waste by 2030 and is relying on waste-to-energy solutions in Sharjah and Abu Dhabi. Oman has adopted a revised derived fuel (RDF) model and waste-to-energy plants (Wang et al, 2024). Alsulaili et. al (2024) study found that environmental and health considerations take priority over cost in Kuwait. This study shows that Bahrain shares with island nations the challenges of limited space and high reliance on landfills, reinforcing the importance of a regional shift towards a sustainable management model based on recycling and waste-to-energy, as demonstrated in the experience of the UAE and Mauritius (Wang et al, 2024).

1.2.3 Assessment of landfill leachate emission from fresh MSW

Unscientific dumping of waste is a major problem in quantifying, measuring, treating and monitoring leachate across the world. Venkatesh et al. (2020) conducted a study in India to investigate the degradation of MSW and found that the concentrations of leachate variables were high, and sedimentation had a direct impact on the quality of leachate. Samadder et al. (2017) studied the

impact of leachate from unregulated landfills in India, where they took groundwater and soil samples from 15-meter-deep pits and observed the presence of some toxic metals in groundwater, soil, and surface water samples.

1.2.4 Study the current situation and find the possibilities.

Open landfill is the widespread practice of MSW disposal in the Kingdom of Bahrain. This practice poses significant environmental and health risks due to emissions of toxic and GHGs through direct combustion and/or decomposition of waste. Therefore, there is an urgent need for integrated solid waste management (ISWM) using a method appropriate to the environment of the Kingdom of Bahrain and the available economic possibilities so that it is feasible and reduces the landfill to reduce the amount that is buried lightly on Askar landfill, which has expired, to benefit from the waste and be able to recover the materials and enable the sanitary landfill.

Accordingly, a set of scenarios will be studied for the state of waste management by maintaining the weighting of the 2030 SDGs in the world. During this, waste management methods are studied and evaluated, and the influencing factors and obstacles that prevent the implementation of these methods are identified. The future of waste is studied in the world, and what will happen to the earth due to the increase in waste and its impact on the environment and the future of the world. This study attempts to develop solutions and proposals to reduce waste, reduce pressure on landfills, and affect the environment through codifying technologies, enacting legislation, and monitoring populations. Through research and comparison, it is found that formal handling and treatment of ISWM would reduce landfilling, as LCA could be the panacea for achieving SDGs.

1.3 Research Questions

Here is the research questions related to the research problem that need to be answered through this study. Main question: What is the optimal model that achieves sustainable waste management for efficient treatment and assists in waste management planning that achieves SDGs related to MSWM? The four questions are:

1. How can the current performance of MSWM in Bahrain be described using LCA, and how do these compare with international environmental standards?
2. To what extent have SDGs No. 11, 12, and 13 been achieved in the current MSWM in the Kingdom of Bahrain, based on LCA results? How can those goals be achieved?
3. What are the appropriate tools, administrative alternatives, and opportunities that support decision-makers in determining the best MSWM policy that leads to improved environmental results at the lowest costs through comparative life cycle evaluation?
4. What are the appropriate technologies to be used in MSWM to reach the best environmental outcomes at the lowest life cycle costs?

1.4 Research objectives

This study aims to propose a sustainable model for MSWM in which the environmental impacts of MSW in the Kingdom of Bahrain are evaluated to choose the best approach for Bahrain society. The facts are studied from various social, economic, environmental, and technological aspects, and the opportunities and challenges are studied to help decision-makers identify

tools, opportunities, and administrative alternatives to improve environmental outcomes at the lowest cost.

The objectives of the study have been clearly and precisely defined, and they are the result of the research questions that were mentioned previously. These objectives are written as procedural points according to the research questions and are related to the variables that the researcher aims to approach.

Overarching Aim: Developing a model for sustainable waste management that facilitates planning and effective use of waste management to achieve the SDGs.

1. To describe the current performance of MSWM systems using life cycle assessment and find the best practices for achieving environmental sustainability.
2. To assess the extent to which direct SDGs 11, 12, and 13 and indirect SDGs have been achieved, through assessing the practical achievements.
3. To determine appropriate tools, administrative alternatives, and opportunities that support decision-makers in defining the best MSWM policy that leads to improved environmental results at the lowest costs, through using LCC.
4. To propose the appropriate technologies to be used in MSWM to reach the best environmental practices with the lowest costs, based on life cycle modeling and scenario analysis.

The objective and scope of the study are to assess the environmental impacts of waste management in the Kingdom of Bahrain. The study's function is to determine the life cycle of the activities followed by waste management from the collection of homes and subsequent transfer to landfill until final disposal.

1.5 Research Significance

This study aims to achieve expectations that benefit the environment and contribute to achieving the SDGs. It contains practical benefits that have not been explored before in the Kingdom of Bahrain, including these expectations:

1. Compare the results of the extent to which SDGs related to MSWM are achieved for current and hypothetical systems.
2. Improve the quality of MSW treatment and reduce its quantity.
3. Supporting the environmental, economic, and social pillars of sustainable development.
4. Contribute to mitigating GHG emissions by finding ways to reduce waste and developing sustainable disposal methods, thus mitigating the effects of climate change.
5. Evaluate the decision in finding ways to facilitate waste reduction at the source.
6. Provide a solution to the problem of waste congestion in landfills.

This study supports policymakers in making science-based decisions by assessing the environmental, economic, and social aspects of waste management models using LCA and LCC. It also contributes to guiding infrastructure investments, aligning them with Bahrain Economic Vision 2030 and SDGs (11, 12, 13), and improving municipal waste operations. It also promotes public-private partnerships, raises community awareness of recycling, enriches waste management literature in the GCC, and enhances environmental governance in Bahrain and national knowledge base.

1.6 The Importance of the Topic and Its Universality

MSWM is one of the basic services provided by municipal authorities in both developed and developing countries due to its great importance in maintaining the cleanliness of urban areas (Abubakar et al., 2022; Maity, 2018). Due to modern civilization, the presence of luxury and the tendency towards luxuries in our daily lives with all means of comfort, this life has made us contribute to the production of a large amount of garbage that must be considered (Maity, 2018). MSWM is a critical issue at the global level, and it should be of concern to everyone, as the danger spreads to everyone (UNEP, 2017; Al-Ansari, 2012). It is a serious challenge facing modern societies and harms human health as well as the environment in general (Zafar, 2016; Abubakar et al., 2022). With urban expansion and population growth, the waste problem has spread, and the problem has increased due to improper waste management. This problem is considered one of the most common causes of urban environmental degradation. The phrase “better than waste” has become a reality rather than a theory as tons of solid waste are being used in municipalities and towns in India (Soni et al., 2016). Some argue that the term waste should be called raw material, as it can be converted into valuable products. With population growth more than doubling, there has been a positive relationship between waste generation and income level (World Bank, 2025). Therefore, daily waste generation in high-income countries is expected to increase by 19 percent by 2050. In low-income countries, the total amount of waste generated by 2050 is expected to more than triple, as shown in Figure 1.2. Most of the world’s waste is generated by the East Asia and Pacific region, which is estimated at 23 percent, and the least by the Middle East and North Africa, which produces only 6 percent. Sub-Saharan Africa,

South Asia, the Middle East, and North Africa are the regions experiencing the fastest growth in waste, with total waste generation expected to more than triple by 2050. Due to unsustainable waste disposal and the exponential growth of waste, it will have enormous impacts on the environment, health, and prosperity, so urgent measures must be taken to save the environment. The reasons for the difficulty of MSWM in Bahrain are high population, rapid industrialization with limited land availability, high waste generation growth rate, unorganized SWM sector, scarcity of waste disposal sites, and poor public awareness (Zafar, S., 2023).

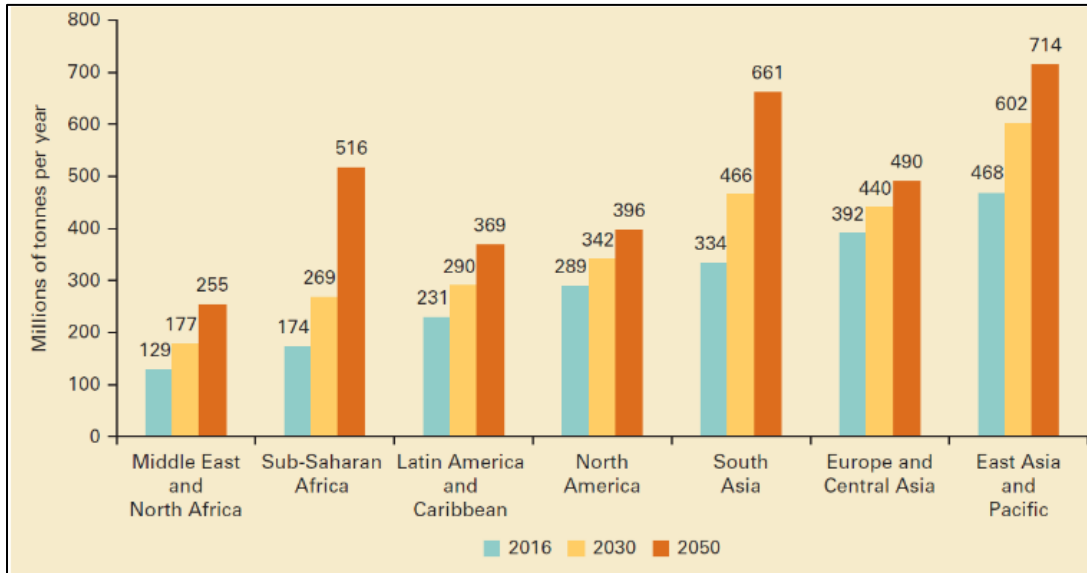


Figure 1.2: Projected waste generation, by region (millions of tons/year)

(World Bank, 2025)

1.7 The study's setting

The study highlights the status of MSWM in the Kingdom of Bahrain. It is an archipelago in the middle of the Arabian Gulf in the Asian continent, with a

limited area and population. Its capital is Manama. Its climate is hot in summer and moderately cold in winter. It has one MSW landfill located in the Askar area in the south of Bahrain. Waste is collected from homes in the four governorates and transported to the Askar landfill. Waste is thrown into large holes in the Askar landfill, which are made and then filled with waste and buried in sand. This method has been prevalent for many years, and according to previous studies, the expected lifespan of this landfill has expired.

1.8 Scope, limitations, and boundaries of the study

This study assesses MSWM in Bahrain from an environmental, economic, and social perspectives, focusing on residential and commercial waste within national borders. The study excludes hazardous, medical, and electronic waste, as well as informal recycling activities. While priority was given to local data, international databases were used when necessary. These limitations help define the scope of the study, contributing to realistic conclusions and highlighting the need for better data and broader future research.

1.8.1 Current Status of MSWM in Bahrain

The study evaluates the status of waste management from an environmental perspective and explains the most important environmental impacts it causes and the damage it causes to humans and the environment. The study identifies the challenges and the possibility of transforming these challenges into fruitful opportunities for the Bahraini economy, with a focus on the benefits and positives for the environment.

One of the most important challenges facing the Kingdom is to evaluate the current situation and find alternatives to traditional methods of burying waste that consume this land and the environment, including the small size of the country, high population density, and high land prices. The main map in Figure 1.3 shows the location of the four governorates that make up the Kingdom of Bahrain. The attached map to the left shows Bahrain's location in its regional context.

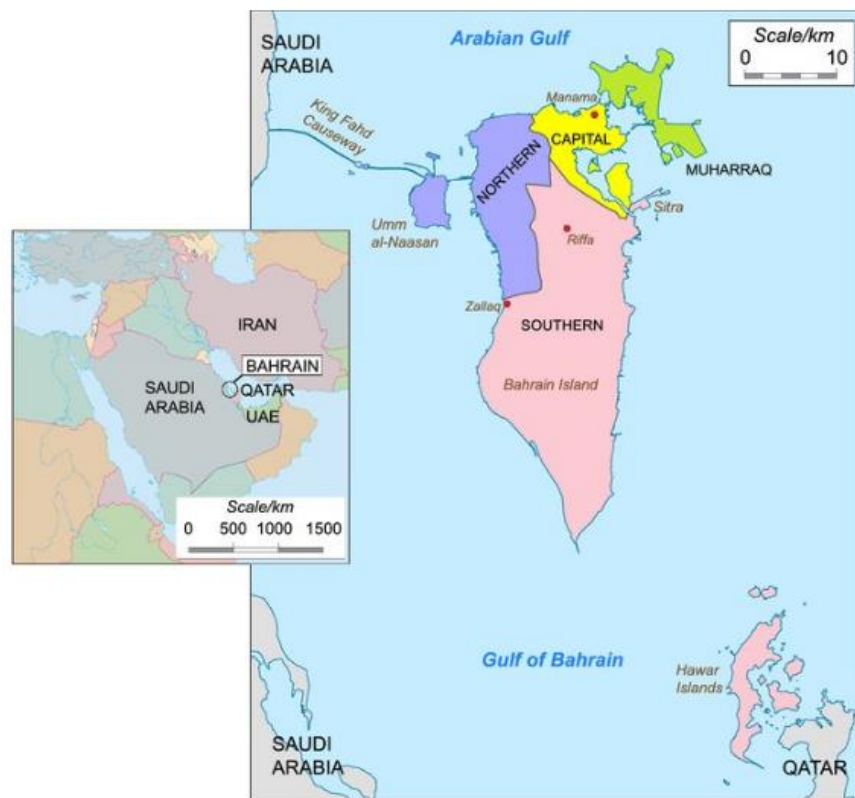


Figure 1.3: Governorates of Bahrain map.

Source : (Al-Snan et al., 2020)

1.9 Research terminology

The following section is for an explanation of the most important terminologies in the thesis:

1. **Acidification:** Acidification refers to an increase in acid content in water and soil, often due to anthropogenic factors (Harkiolakis, N., 2013). Acidity causes fish kills and forest degradation, destabilizes anaerobic digestion, and affects agricultural productivity. It is measured in moles of hydrogen (mol H^+ eq) and can lead to fish mortality and forest decline (EPLCA, 2024).
2. **Eutrophication:** It is the buildup of nutrients like phosphorus and nitrogen in aquatic ecosystems, mainly from agriculture, industry, and livestock waste (Britanica, 2024; Akinnawo, S. O., 2023). It degrades freshwater resources and fisheries (Britanica, 2024). Impacts are measured in Mole N eq, kg P eq, and kg N eq (EPLCA, 2024). Mitigation includes chemicals like lime and ferric sulfate (Akinnawo, S. O., 2023).
3. **Functional Unit (FU):** Since the definition of the objective varies depending on the study, it is necessary to choose the appropriate FU for the study to be compatible with the objectives. The FU can be defined based on generation, disposal, or output. The most common unit used is one ton of MSW.
4. **Global Warming Potential (GWP):** It is also called GHGs or climate change. Anthropogenic GHG emissions arise from many waste processes. These waste gases affect the climate and lead to thermal emissions (Chen et al., 2020). An increase in this indicator indicates an increase in average global temperatures due to GHG emissions (EPLCA, 2024). GHGs, including carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4),

contribute to GWP and are produced during waste management and disposal (European Commission, 2001; Paul et al., 2024).

5. **Human Toxicity Potential (HTP):** Human toxicity indicators assess health risks from air, water, and soil contamination, measured in the Comparative Toxic Unit for Humans (CTUh) using USEtox (EPLCA, 2024). Living near landfills increases the risks of birth defects, respiratory issues, and mental health problems (Romeo et al., 2022; Vinti et al., 2021).
6. **Integrated Solid Waste Management (ISWM):** It is a comprehensive approach to MSWM that combines waste prevention, recycling, composting, energy recovery, and landfilling. It prioritizes sustainability, minimizes environmental impacts, and optimizes resource use through systematic waste handling and policy interventions (UNEP, 2024).
7. **International Organization for Standardization (ISO):** ISO provides key standards for LCA, notably ISO 14040 and ISO 14044, which outline principles, frameworks, and requirements for conducting LCA. These standards ensure consistency, transparency, and comparability in environmental impact assessments (ISO, 2021).
8. **Life Cycle Assessment (LCA):** Evaluates environmental impacts across waste collection, treatment, recycling, and disposal. It helps optimize sustainability by identifying the best waste management strategies, reducing emissions, and improving resource efficiency (ISO 14040, ISO 14044, 2021).
9. **Life Cycle Impact Assessment (LCIA):** It evaluates the environmental impacts throughout the waste management system, including waste generation, collection, treatment, and disposal. It helps quantify effects like climate change, resource depletion, and toxicity, guiding sustainable decision-making.

10. **Life Cycle Inventory (LCI):** It quantifies inputs (e.g., energy, materials) and outputs (e.g., emissions, waste) across waste collection, treatment, and disposal. It helps assess environmental impacts and optimize waste management strategies (EPLCA, 2024).
11. **Municipal Solid Waste (MSW):** Refers to the everyday waste generated by households, businesses, and institutions, including organic materials, paper, plastics, metals, and glass. It is typically managed through collection, recycling, disposal, and treatment methods, impacting urban sustainability and resource recovery.
12. **Municipal Solid Waste Management (MSWM):** It plays a crucial role in achieving SDGs, particularly SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production). Effective MSWM reduces environmental impacts, promotes resource recovery, and enhances public health.
13. **Urban Land (Agricultural land occupation):** With the expansion of the population of more than 7 billion people and unsustainable consumption and production, land became a problem due to increasing pressure on land, which generates environmental problems (Oosterhoff & Kootwijk, 2020). LCA considers land area, its uses, and measurements for production purposes to reduce land depletion. (Oosterhoff & Kootwijk, 2020). Land-use change can lead to loss of functions, health issues, ecosystem degradation, and resource depletion. The Urban Land Index measures soil properties, while the Urban Land Carrying Capacity study explores sustainable development and carrying capacity in cities (Yang & Zheng, 2010).
14. **Water depletion:** Water depletion impacts sustainable development and environmental protection due to improper waste disposal, causing contamination of water sources and affecting human health and ecosystems.

15. Sustainable Development: The Brundtland Commission defined sustainable development as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987).

1.10 Vision for Integrated MSWM and Zero Waste

On March 27, 2024, IGES and UNEP (2024) discussed the path to achieving zero waste in a symposium about SWM Towards Zero. The symposium recommended raising stakeholders' awareness of the critical role of zero-waste cities in sustainable urban development. Integrated MSWM requires a balance of performance within technical, economic, and social constraints (Abeliotis, K., 2011). As the Earth's population grows and developments in various aspects occur, the world's resources are threatened by pollution and climate change because of municipal and industrial processes. Therefore, sustainable waste management is crucial, as it will alleviate the environmental burden on the Earth and reduce environmental impacts (Öztaş, S., & Bektaş, N., 2021).

1.11 Summary of Chapter 1

This chapter introduced the research by contextualizing the challenges of MSWM in Bahrain, highlighting the environmental, economic, and social consequences of current waste practices. It emphasized the need for a comprehensive approach guided by LCA and LCC, introducing the SELECT model as a conceptual framework. This chapter laid the foundation for the first objective by defining the scope of the problem, justifying the study's significance, and articulating the four objectives.

Chapter 2. Theoretical Framework and Literature Review

2. Introduction

This chapter provides a theoretical overview of MSWM. This is followed by a review of previous studies related to the research topics. The chapter concludes with a summary of the findings, including the research tools, methodology, procedures, and hypothesis formulation. Finally, the study's hypotheses are stated.

2.1.1 The concept of MSWM

Waste is any resource that is not a primary product (i.e., goods created for the market), which the producer discards, plans to discard, or is forced to trash because they are no longer needed for production, transformation, or consumption (Ghafari, D., 2022). EPA (2019) defines MSW as the components of everyday items that are used and then thrown away, such as product packaging, furniture, lawn and food clippings, bottles and cans, clothing, newspapers, electronics, batteries, paint, and various appliances.

2.1.2 Waste hierarchy

The European Union established the Waste Framework Directive in 2008. Figure 2.1 shows the top priorities they recommend applying to all waste (Nehrenheim, E., 2013). The EU hierarchy prioritizes waste minimization, which essentially means that any improvement of resources should be considered waste management. This comes through two systems, namely material reuse and waste recycling. The waste management sequence is based on four basic elements: reduce, reuse, recycle, and recover. (World Bank, 2012).

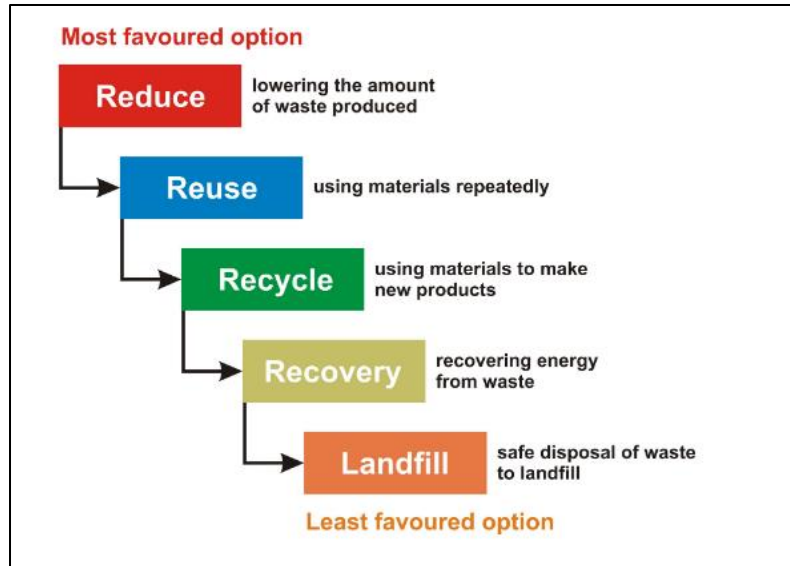


Figure 2.1: Waste hierarchy.

(Source: <https://www.pinterest.com/pin/809873945465351295/>)

2.1.3 Prevention and treatment

Food waste, estimated at 34% in the Near East and North Africa region, contributes to food insecurity, increases waste, and exacerbates environmental impacts (FAO, 2015; 2014). Raising public awareness of sustainable consumption through stakeholder collaboration and community engagement contributes to reducing food waste (Al-Zahrani & Beg, 2014). The hospitality sector's development of lunch waste reduction strategies plays an important role in limiting and improving buffet-style changes (Capone et al., 2016; Abaza et al., 2011; Hwalla et al., 2015; Pirani & Arafat, 2016). Guiding consumers toward sustainable consumption by planning their purchases and avoiding excess or unnecessary purchases contributes to reducing food waste and promoting the optimal use of food scraps (composting) (Questa et al., 2013). Food waste can be recycled and converted into products such as fossil

fuels, biochar, fertilizers, and chemicals (Al-Ansari, 2012; Al-Maaded et al., 2012). Optimal use of waste through composting also contributes to economic, environmental, and development benefits (Waqas et al., 2018).

2.1.4 Hazardous waste

Waste is considered hazardous when it is flammable, undergoes a chemical reaction, comes into contact with other wastes, is damaged by other compounds upon contact, or is toxic to living organisms (EPA, 2022). It must be handled carefully and removed from circulation to ensure a safe environment and the safety of people now and in the future (Fortum, 2021). Household waste contains many heavy metals or hazardous materials, so it is important to know how to dispose of it properly so that it does not pose a risk to people and the environment (Hennepin County Public Works, 2017). Policymakers and executives should consider this by preparing workers when handling and processing household waste.

2.2 LCA Methodology for MSWM

The general scope of LCA research is explained in this section. The system boundaries and internal and external flows are also determined. Brief information about LCI and LCIA. To find out the differences in MSW flow and compositions for the Bahrain case, all available information was tested in OpenLCA.

The LCA approach will be chosen to assess the environmental impacts of MSW, using OpenLCA software. R and Excel will be used to analyze data and generate graphs. R software is a free, open-source programming language and designed for statistical computing, data analysis, and graphical representation.

This will help us determine the appropriate MSWM strategy for the local practice. The LCA method is characterized by reliability and data quality (Iqbal et al., 2020). LCA policy calls for identifying best practices in MSWM based on effective proposals. The most common and comprehensive methods focus on greenhouse gas emissions or water use (Blanco et al., 2015). LCA methodology is characterized by understanding and analyzing the holistic picture, considering the economic, environmental, and social consequences (Parvathy et al., 2025). Work on LCA has focused on waste management activities in Europe, and to a lesser extent in developing countries (Laurent et al., 2014). The LCA approach is often used in high-income contexts to assess MSW. It is rarely used in developing countries due to a lack of financial resources and technical capacity (Ferronato et al., 2020). The reliability of LCA results is affected by geographical data. Ferronato and Torretta (2019) argue that because of the significant utility of LCA approaches, low- to middle-income countries should be encouraged to develop waste management.

The product life cycle is a method for evaluating a system, service, or product's possible effect on the environment (ISO 14040). Because LCA begins by studying everything from beginning to end, it's known as "cradle to grave" (DEAT, 2004).

LCA is an important method for measuring environmental impacts and costs and comparing different waste treatment scenarios (R. Abu et al., 2023). LCA is useful for identifying and tracking environmental footprints, guiding decision-making, and achieving SDGs. It enables comparison with alternatives, enables waste management stakeholders to identify problems,

and can propose improvement options adapted to the local situation (Laurent et al., 2014).

System boundaries are essential to the LCA model. The system boundaries are defined by the processes, interactions, and activities included in the analysis, as well as the inputs, outputs, and environmental impacts to be measured. The reasons for adding or removing any process or step from the system are explained at this stage (ISO, 2006b). The European Commission (2010) recommends displaying a flow chart to represent the process flow in the system and highlight its boundaries in terms of adding or removing a process or parameter.

Differences in perspective, perception, and the requirements of each study make matters uncertain, so making assumptions shapes the course of analysis. Making assumptions by including or excluding a particular process or unit from the analysis leads to several possibilities, including 1) a negligible impact on the overall results; 2) an equal impact before or after entering the system; and 3) assumptions may be made due to a lack of data (Iqbal et al., 2020).

The study requires collaboration with local stakeholders. It also requires access to local solid waste treatment facilities and final disposal sites, and collaboration to exchange information and expertise. This collaboration includes expert interviews, field inspections, and attendance at workshops and conferences. Defining the system boundaries and scope is a major challenge when using LCA. Challenges include the availability of necessary data, defining flows, and identifying the most significant environmental impacts. Lack of expertise in LCA is another challenge facing users of this method.

Figure 2.2 illustrates the main users of LCA: industry and other businesses, national governments and local, national, and intergovernmental regulatory bodies, non-governmental organizations, and consumers.

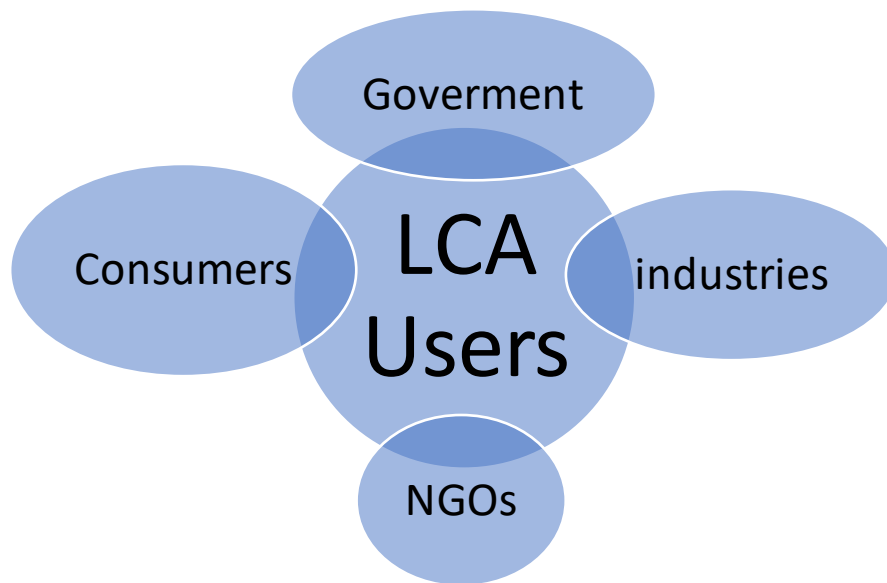


Figure 2.2: LCA Users. (Graph created by author)

Assessments are essential tools for linking science to decision-making. There are various metrics for measuring any impacts from emissions, costs, etc., such as carbon footprint, and in the assessment criteria, the desired impacts should be specified (Levis et al., 2016).

An Environmental Product Declaration (EPD) provides information about the potential environmental impact of a product on the environment and human health and is a shortened version of an LCA report without sensitive details about the company (Echochain, 2022).

LCA software and databases contribute to the speed and reliability of data analysis (Iswara et al., 2020). Commercial software is available with annual subscriptions, while free software provides services to scientists and researchers, providing parts of the databases with limited functionality (Ferronato et al., 2020). These programs perform complex calculations in a systematic manner (Iswara et al., 2020). There are general software models that can be used in LCA for any product or service, such as SimaPro and GaBi. Later, there are programs specifically developed for LCA of waste management (such as EASETECH, SIWMS, WRATE, and IWM). The service in waste is considered an input, not an output, and is calculated negatively, while the output is positive as a product of the treatment process, to maintain the mass balance of the process, as shown in Figure 2.3.

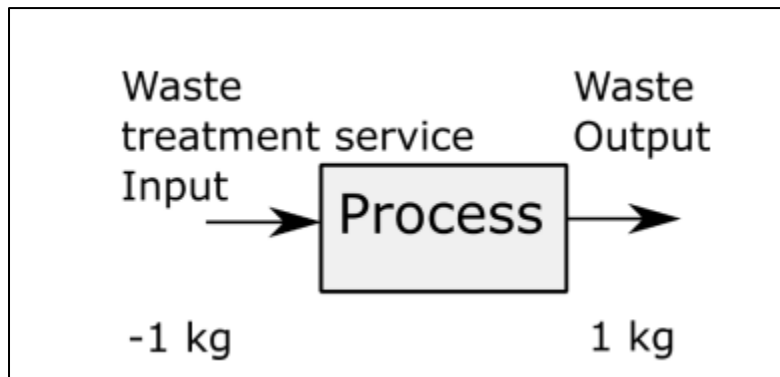


Figure 2.3: Representing waste treatment in LCA.

2.3 LCA Optimization

Although assessment and optimization in the LCA method are similar, there is a distinction between these two types. The former is characterized by being a systematic and comprehensive analysis that considers all stages of the life cycle, as mentioned in chapter 1, and it helps in identifying the main

environmental impacts. Optimization is identifying strategies to reduce the environmental impacts of a system, process, or product. This stage is based on the results of the assessment stage and focuses on improving environmental performance. Optimization methods can be through comparing alternative products or services, and they also play a role in achieving optimal solutions (Crippa & Ugaya, 2023).

2.3.1 The Significance of Optimization

Optimization contributes to optimal solutions and supports decision-makers by allowing the integration of technologies into the optimization process to select the best design from a range of alternatives for developing a product or service (Alsabt et al., 2024). LCA contributes to achieving a balance between environmental conservation and economic empowerment, highlighting cost savings through the efficient use of resources by improving supply chain management and reducing energy and material consumption (Yu & Li, 2024). Advanced technologies, such as AI, contribute to improving waste management systems, reducing collection and treatment costs, and improving public practices (Boudanga & Medromi, 2023). IoT-assisted optimization reduces environmental impact by monitoring garbage bins and optimizing waste truck routes by up to 20% of the resources used (de Barros et al., 2022).

2.3.2 LCA and MSWM Options

The LCA method is used in many countries to evaluate different strategies for MSW and assess treatment options (Ghosh et al., 2020). The LCA method helps in preventing pollution and reducing resource consumption by studying the entire life cycle of waste. The LCA method helps in identifying the most environmentally friendly option for the MSWM system.

2.3.3 Modelling in MWSM

One of the goals of modeling is to gain insights or analyze the behavior of a system, and one of its forms is the conceptual framework (Collin, 2023). Modeling is used to guide decision making, solve problems, develop policies, or improve processes. To define a conceptual framework model, the variables and processes in the model must be identified, as well as the purpose of the model. Second, the literature must be reviewed, and similar models identified that can help define the variables. Third, stakeholders with expertise in the system under study must be identified and involved in the model. Fourth, the necessary data must be provided with the required reliability and level of detail. Fifth, a sensitivity analysis must be conducted to assess the impact of the variables on the model's output. Sixth, researchers must balance the identification of all factors with the feasibility of analysis, interpretation, and practical management (Quimby & Beresford, 2023; Neslo & Cooke, 2011; Pluchinotta & Zimmermann, 2024; Ten Broeke & Tobi, 2021).

2.4 Literature Review of LCA for Studying the MSWM

The literature on MSWM reveals a diverse range of approaches, tools, and contextual considerations, which can be grouped thematically to highlight methodological trends and existing research gaps. A dominant methodological approach in many studies is LCA, widely used to evaluate environmental impacts across different waste treatment scenarios. For example, Al-Salem & Lettieri (2009) employed LCA to compare three MSWM scenarios in Kuwait and found that anaerobic digestion yielded the lowest global warming potential. Similarly, Abeliotis (2011), Saheri et al. (2012), and Batool et al. (2023) identified anaerobic digestion and composting as environmentally

superior options in Malaysia and other contexts. LCA was also central to Bernstad (2010), who emphasized the role of household waste segregation in Sweden and demonstrated how LCA can guide policy decisions. Bala et al. (2015) and Yay (2015) further supported the role of LCA in determining optimal treatment methods, while Damgaard et al. (2011) and De Feo et al. (2016) highlighted the influence of facility proximity and engineering design on environmental performance.

In terms of geographic context, the studies span a wide range of countries—from Malaysia (e.g., Saheri et al., 2012; Alias et al., 2016; Abas et al., 2022) to Cyprus (Erhun, 2022), Australia (Dastjerdi et al., 2021), Turkey (Yay, 2015), Bolivia (Ferronato et al., 2020), Sweden (Bernstad, 2010), Latvia (Puriņa, 2018), and Greece (Baniyas et al., 2020). This geographical diversity reflects both the global relevance of MSWM, and the contextual specificity needed for effective solutions. For instance, Hettiarachchi et al. (2018) demonstrated that socioeconomic factors in Latin America play a crucial role in MSWM outcomes, while Dubey et al. (2020) introduced smart technologies in India to promote segregation and optimize waste collection.

Another critical theme is the integration of sustainability dimensions, where researchers have moved beyond environmental analysis to include social and economic considerations. Thyberg and Tönjes (2015) developed a multidisciplinary framework incorporating stakeholder engagement and policy adaptability, while Zhou et al. (2019, 2022) included social resistance and awareness as indicators in sustainability assessments. Mir et al. (2016) and Levis et al. (2014) echoed similar integrative approaches, stressing the need to align technical feasibility with public acceptance and cost. Meanwhile, Alias et al. (2016) and Hettiarachchi et al. (2018) underscored the value of

public-private partnerships and community participation, particularly in contexts with weak institutional capacities.

Thematically, a strong body of literature supports recycling, composting, and anaerobic digestion as preferred treatment options. Studies by Vargas (2014), Mir et al. (2016), Erhun (2022), and Baniyas et al. (2020) all conclude that combining material recovery, composting, and anaerobic digestion can yield optimal environmental outcomes. In contrast, landfilling and incineration, particularly without energy recovery or pollution controls, are repeatedly identified as less favorable (e.g., Yay, 2015; Zhou et al., 2019).

Despite the robustness of these studies, research gaps remain. First, while LCA is widely applied, comparative studies that integrate LCC, stakeholder analysis, and behavioral dimensions are still limited. Second, few studies systematically evaluate policy effectiveness or institutional capacity, which are critical for implementing sustainable systems. Third, although many studies suggest integrated waste management strategies, holistic models that combine technical, environmental, economic, and social indicators within a single decision-making framework—particularly tailored to developing countries—are still scarce. Moreover, while studies such as Ferronato et al. (2020) and Abas et al. (2022) hint at capacity-building and policy reform, actionable guidance for municipalities remains underdeveloped.

In light of these gaps, the current study seeks to contribute by integrating LCA with broader sustainability assessments using the SELECT model, which encompasses Social, Environmental, Legal, Energy, Cost-effectiveness, and Technology dimensions. This approach builds on the strengths of previous literature while addressing the identified need for a comprehensive, context-sensitive framework suitable for regions like the Kingdom of Bahrain.

2.5 Research Gap

Based on previous studies, there is a consensus on the importance of the LCA approach. This approach is used to calculate the recovery of by-products from waste and is a more accurate prediction model for waste collection and outcomes, as it incorporates emissions and waste products. Knowing the quantity and composition of waste is useful in determining its environmental impacts and impacts on humans and the environment. Environmental impact assessments help determine the best ways to protect the environment and humans. Previous studies show that the success and sustainability of waste management depend on several factors, including reducing environmental impacts, reducing energy use, and contributing to waste production.

Legislation helps regulate the process, considering social acceptance. Waste management must be economically cost-effective and generate income through resource recovery. The use of technology contributes to the development and sustainability of waste management and reducing costs and environmental impacts. Conducting an environmental impact assessment contributes to sustainable waste management. Studies have focused on the importance of prevention principles, specifically preparation for reuse, recycling, and recovery, such as energy recovery and disposal. The choice of treatment technology depends on a study of environmental, economic, and social impacts.

Awareness plays a crucial role in waste reduction and the successful use of the correct method. Composting should be encouraged, and cooperation and stakeholder engagement are essential to successful management. The success of the optimal method depends on its diversity and suitability for each region,

as well as the need for strategic planning, financing, and the use of smart technologies and systems.

2.6 Good MSWM Practices

This section reviews some of the good practices of the successful countries in the world that have achieved remarkable progress and received international awards for their successes. The UNEP (2017) report mentions a group of countries that have achieved best practices and have a strong approach to waste management.

Osaka, Japan, built its massive waste incinerator and created a recycling system that turned it into electricity for 125,000 homes. Alappuzha, in the eastern Indian state of Kerala, launched a campaign to solve all its waste problems and drawbacks. The campaign introduced a decentralized system for separating waste, using and processing it in small composting plants, and providing biogas to serve its residents.

Ljubljana, Slovenia, opted for maximizing recycling and reducing waste, achieving the highest rates in Europe - over 60% - and receiving the "Green Capital" award from the European Assessments in 2016. It encouraged people to separate waste for their benefit, increased the amount of recovered materials, and achieved the lowest average waste management cost. Cajica, Colombia, initiated its waste recycling campaign, reducing tons of landfill waste by a quarter. It adopted a circular economy policy, relying on ongoing awareness-raising and encouraging households to separate their waste before collection. It invests approximately 350 tons of organic waste in composting.

Germany follows a policy of separating waste and converting it into clean, renewable energy. The waste industry contributes approximately four billion euros to the German economy annually and is a renewable energy source. Germany converts waste after recycling into energy, where tens of tons of waste are burned and converted into thermal water that produces steam to generate electricity. The German government imposes strict laws on non-compliance with the waste sorting system (DW Academy, 2013). South Korea's waste management system focuses on minimizing waste production and maximizing recycling. The waste management law and hierarchy minimize general waste and impose a volume-based fee system for all types of waste (Figure 2.4).

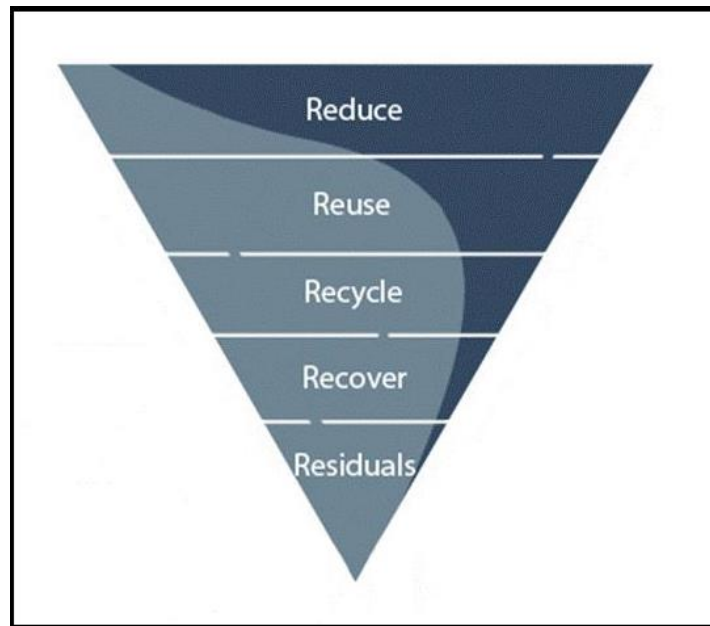


Figure 2.4: Waste management hierarchy adopted in South Korea.

Source: Wikipedia (2023).

2.7 Global models in MSWM

In this section, the research reviews some models of successful countries that have achieved the best and most sustainable models according to international standards.

2.7.1 Global models of waste recycling

Xevgenos et al. (2015) suggest adopting specific recycling practices and source segregation schemes for sustainable MSWM. Factors affecting recycling performance include curbside collection schemes, economic incentives, legal instruments, public awareness, population size, and implementation duration. Easy access to recycling systems and segregation of organic materials at the source are crucial for higher recycling rates.

2.7.2 Advanced Local Model: Participation in MSWM

Basu & Punjabi (2020) present an advanced model for city cleanliness, focusing on community partnerships and civic groups in waste management. The Advanced Local Model (ALM) program began in an Indian village and has since expanded to include the entire city and its residents. The program's experiences highlight the importance of inclusiveness and collective participation among leadership and grassroots committees. Official support is crucial, and officials should reward volunteers with incentives. The vision should engage citizens and civic bodies and support innovations to engage more citizens in local governance.

2.8 MSWM sustainability

Poor MSWM threatens the environment, public health, and economic and social issues due to rapid urbanization, population growth, and improving living standards (Malav et al., 2020). Sustainable management helps preserve the environment and reduce pollution (Öztaş & Bektaş, 2021). Environmental sustainability and waste management are interconnected, requiring global cooperation and a comprehensive management plan to reduce waste production and implement waste treatment programs (Goodland, 2002). Improper solid waste management negatively impacts the environment and terrestrial ecosystems, with approximately 50 large open dumps across five continents and projected annual carbon dioxide emissions of 2.38 billion tons by 2050. Despite being neglected during industrial and economic development, the 17 SDGs, their 229 targets, and 247 indicators outline how to make waste management sustainable (ISWA, 2016; Liu et al., 2015; de Barros et al., 2022). The following section discusses the relationship between sustainability and waste management in detail and provides tips and guidelines for improving the MSWM situation in Bahrain.

2.8.1 Sustainable Elements to MSWM

This research addresses the most important proposed elements that contribute to the sustainability of MSWM.

2.8.1.1 Social acceptability

Participation in waste management between authorities and the community is essential and should be given attention and continuous communication (Hilles, A. H., 2011; Abubakar et al., 2022). The role of local authorities is to

spread awareness through awareness campaigns, clarify roles, and make homeowners understand the importance and reason for doing so. When some residents have barriers, waste managers play a role in overcoming these barriers and finding alternatives. Therefore, to determine the waste treatment system, it is necessary to choose an integrated, effective, and sustainable system that should be fully implemented in collaboration with the public, local authorities, and the private sector. community participation is key in MSWM (Mozhiarasi & Natarajan, 2022).

2.8.1.2 Environment protected.

Waste poses a burden to humanity and the planet. It is a source of negative environmental impacts and affects the climate due to the gases it produces, such as methane, which is 25 times more potent than carbon dioxide (CO₂) (FAO, 2013; Zhang et al., 2019). Recycling waste reduces the amount of landfill waste sent to landfills, is useful in producing biochar and fertilizers, and leads to climate change mitigation (El Bilali & Ben Hassen, 2020). Disposing of food waste in landfills represents a missed opportunity, in addition to contributing to greenhouse gas emissions and soil pollution, not to mention the unpleasant odors in the areas surrounding the landfill (Shahzad et al., 2017).

2.8.1.3 Legislation (Regulatory, Administration, and Policy)

The mandatory practice of effective waste management at the public, community, and corporate levels is essential to reduce the depletion of natural resources and bring out the concept of a circular economy for waste management (Mozhiarasi & Natarajan, 2022). Policy plays an important role in influencing the sustainability of MSW management, especially in the aspect

of adequate legislation. The intervention of local authorities and building incentives for residents greatly improve the level of MSWM (Xin & Wan, 2023). Laws and regulations play a major role in ensuring a comfortable environment for residents through efficient management of waste production and consumption (Ivanova & Lisina, 2023).

2.8.1.4 Energy efficient and productive

With the accumulation of waste and its negative environmental impacts, the thinking came about how to manage it properly and sustainably, with the need for energy in general and renewable energy in particular, the thinking came about converting waste into energy (Malav et al, 2020). Converting waste to energy is considered a desirable means of obtaining renewable energy sources and biogas, while also being a solution to reduce pressure on landfills and eliminate many environmental problems (Malav et al., 2020). Solid waste is also considered a potential resource for recovering many value-added products and renewable energy (Mozhiarasi & Natarajan, 2022).

2.8.2 Cost-effective

The development of MSW sustainability must consider economic as well as environmental aspects. The economic evaluation of waste management is an important consideration before studying the waste management system (Greco et al., 2015). Waste is a resource that can be exploited rather than wasted, and the more sustainable it is, the lower its cost (Öztaş & Bektaş, 2021). Economics helps convert waste into raw materials, save energy, maintain consumer satisfaction through new materials from waste, and increase employment opportunities. The European Union has set recycling targets of at least 65% and a maximum of 10% of MSW landfills by 2030 to

stimulate the circular economy. The use of LCA helps improve waste management systems, urban development, and achieve the circular economy and sustainable development (Ferronato et al., 2020).

2.8.3 Technology innovations in solid waste control

Waste segregation is of great importance to sustainable waste management, and its development is considered a necessity due to the difficulty of manual sorting. Therefore, technology using infrared sensors comes into play (Shekdar, 2009). Intelligent methods of computer-programmed robotic machines are used to utilize recycling technologies for sustainable waste management (O'Connor, 2017). A software model is needed to develop highly efficient processes and technologies in MSWM (Öztaş & Bektaş, 2021). Waste classification and assessment of its components help determine the appropriate category, and the use of modern technologies facilitates its handling or transportation for accurate sorting and analysis (Fortum, 2021).

2.8.4 Artificial Intelligence

Recently, AI technologies have played an important role in solving solid waste problems. Among the solution areas that AI has entered are solving environmental pollution issues, logistics, waste management, and planning MSW strategies (Abdallah et al., 2020). Some of the uses of AI to improve the waste ecosystem include converting waste into energy, using smart bins and waste sorting robots, monitoring and tracking waste, illegal dumping, saving costs, and improving public health. Fang et al.'s (2023) study indicates that using AI can reduce transportation distance by up to 36.8%, save time by up to 28.22%, and save costs by up to 13.35%. The same study indicates that using AI in waste sorting has an accuracy of up to 99.95%.

2.8.5 Internet of Things (IoT)

The Internet of Things (IoT) technology enables the reading and transmission of container-sized data through the Internet via sensors (Abdullah et al., 2022). Using IoT in containers and trucks to identify and separate excess waste, use an optimization algorithm, and find the optimal route reduces costs for the government. Through IoT, waste production volume can be determined, thus determining the number and size of trucks and dispatching trucks to relevant locations. The IoT system helps reduce the number of truck visits to smart sites and bins, saving effort, time, and cost. When this waste is invested and controlled through a smart waste management oversight platform, it will contribute to the circular economy (Wu et al., 2022).

2.9 Relationship of MSWM with SDGs

Sustainability is defined as meeting current needs without affecting the ability of subsequent generations to meet their needs (Öztaş & Bektaş, 2021). It aims to achieve well-being for all people and improve their quality of life. Sustainability is linked to every step in our lives, from manufacturing to transformation to customer service to disposal, and if we preserve the environment and protect the earth and all living things. Sustainability covers three pillars: economic, social, and environmental justice. To achieve a balance in the decision-making process, the three pillars of sustainability, namely the environment, economy, and society, must be considered (Al Lahou & Alsabbagh, 2019). Zhou et al. (2022) in their study developed an indicator system for the sustainability of MSWM. The indicator system is based on the standard indicator framework “Waste Awareness”, which consists of four

dimensions: the value of the resources, the environmental impact, the economic feasibility, and the social aspect.

2.9.1 Direct SDGs with the subject of waste

The research addresses the direct objectives of sustainable development and their relationship with waste management, and their impact on achieving progress and sustainability in waste management. Table 2.1 shows the indicators of SDGs directly related to waste. The benefit of these indicators is that they provide a clear measurement tool for tracking progress in reducing waste, increasing recycling, and improving waste management. They also support informed decision-making by governments and stakeholders through quantitative and standardized data. They also enhance accountability and international partnerships, driving the implementation of more efficient and environmentally and socially sustainable policies.

Table 2.1: Indicators of SDGs related to MSWM.

11.6.1	• Municipal Solid Waste Management.
12.3.1	• Food Loss and Waste.
12.4.1	• Information on chemicals and waste agreements.
12.4.2	• Hazardous Waste generated and treated
12.5.1	• National Recycling Rate
12.1.1	• Coastal Eutrophication and Plastic Debris Density
12.3.1 a	• Food loss index
12.3.1 b	• Food waste index
13.2.1	• Combat climate change

2.9.1.1 SDG 11

Goal 11 aims to make cities and human safe, secure, and sustainable by providing clean basic services. The targets for Goal 11 cover areas related to the environmental impacts of cities. Indicator 11.6.1 helps cities and countries better manage resources, mitigate and prevent environmental pollution, help create investment opportunities, jobs, and livelihoods, and stimulate the circular economy. Target 11.3 addresses sustainable urbanization and participatory planning and management, achieved by using land instead of unsustainable consumption, such as landfills, and replacing it with more sustainable methods. Target 11b calls for improved waste management.

2.9.1.2 SDG 12

Goal 12 aims to reduce per capita global food waste. Indicator 12.3.1 measures consumption and ensures the sustainability of natural resources. Those involved in waste management must monitor and measure food losses, which is done through Indicator 12.3.1a. Indicator 12.3.1b measures the amount of food wasted. This allows waste management to identify information that will help decision-makers take action to reduce food waste. Target 12.4 addresses the sound management of chemicals, their collection, and the reduction of their release to air, water, and soil. Indicator 12.4.2 aims to identify the proportion and details of hazardous waste generated. Indicator 12.5.1 aims to significantly reduce waste generation through prevention, reduction, recycling, and reuse.

2.9.1.3 Goal 13

Goal 13 and Target 13.2 emphasize taking urgent and necessary measures to combat climate change, which calls for waste management to study this vital topic to improve methods and innovation in waste management.

2.9.2 Indirect SDGs with the subject of waste

2.9.2.1 Goal 3

The third goal of the SDGs refers to ensuring healthy lives and promoting well-being for all at all ages. This goal is related to MSWM through several health and environmental aspects, as waste management practices affect public health and the quality of the living environment.

2.9.2.2 Goal 8.

The eighth goal is to achieve productive employment, decent work for everybody, and sustained economic growth. Rational and sustainable waste management will contribute to economic growth and job creation if waste is optimally utilized. Target 8.2 calls for achieving maximum productivity through technological progress and innovation, and Target 8.4 refers to improving programs related to sustainable consumption and production, urging us to consider waste reduction.

2.9.2.3 Goal 9

Goal 9 aims to promote inclusive and sustainable industrialization, build resilient infrastructure, and foster innovation, as the production of fast-moving consumer goods increases waste. Indicator 9.5 calls for strengthening scientific research in waste management and urges decision-makers to support

research and development in waste management. Indicator 9b aims to support the development of local technology and waste management needs.

2.9.2.4 Goal 14

Target 14.3 refers to the growth of advanced waste management schemes that help reduce ocean acidification. Therefore, acidification needs to be studied, its degree needs to be known and monitored, and plans developed to control it.

By preventing and minimizing marine pollution of all types, especially from land-based activities like marine debris, Indicator 14.1.1b seeks to lessen the effects of pollution. This index monitors the accumulation of plastic on beaches and oceans and its ingestion by organisms. Plastic can be monitored through consumption and recycling, and the level of human and ecosystem health.

2.9.2.5 Goal 15

Goal 15 calls for protecting and sustaining terrestrial ecosystems, and Target 15.1 refers to conserving inland freshwater ecosystems, which calls for sound waste disposal that does not impact groundwater.

2.9.2.6 SDG 17

To accomplish the goals, SDG 17 emphasizes enhancing partnerships, which involves collaboration between local, national, and international governments, the commercial sector, civil society, and academic institutions. International partnerships advance waste management through international financing, the development of innovative solutions, improved efficiency, economic growth, and training and education in sustainable waste management.

2.9.3 Sustainability in industries and waste management

There is a need for sustainable waste management development due to its role in economic development and community preservation. According to Rashed et al. (2021), to preserve the economy and prevent any negative consequences of environmental degradation, sustainability must be incorporated into industrial development. Sustainable manufacturing drives economic growth and utilizing the product life cycle helps achieve this (De Oliveira Neto, G. C., 2018).

2.9.4 The relationship between ISO and SDGs

There is a relationship between the ISO standards and the SDGs, as is evident in the chart in Figure 2.2, which shows the number of standards in each of the SDGs. ISO contributes to all the SDGs. Figure 2.5 shows the number of ISO standards that are directly applicable to each goal. This relationship provides indicators to decision-makers on the possibility of using quality steps in MSWM.

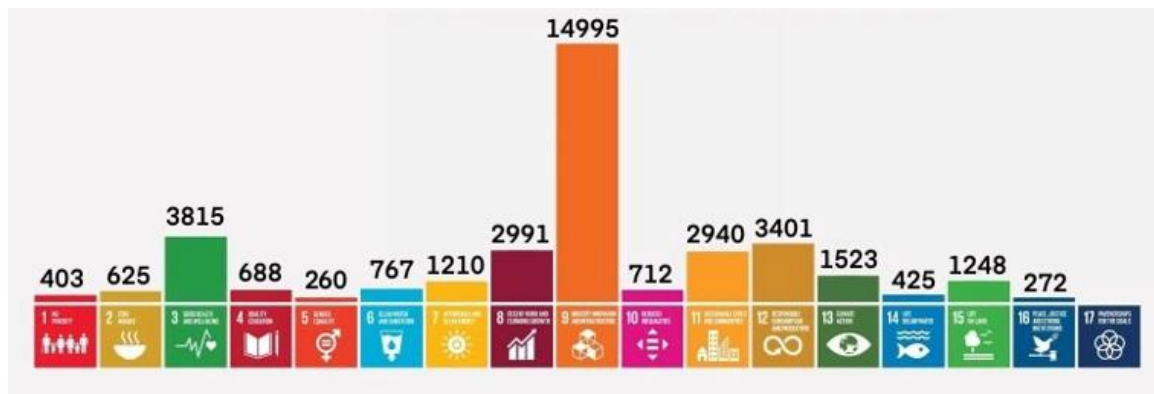


Figure 2.5: Contribution of ISO to all SDGs.

Understanding the relationship between ISO and the SDGs is beneficial, as it provides unified frameworks and standards that help organizations and countries achieve quality, safety, and sustainability in operations, products, and services. This understanding also supports the integration of environmental, economic, and social performance, contributing to balanced and sustainable development. It also enhances trust, transparency, and accountability among stakeholders at the local and international levels. Therefore, understanding this relationship contributes to improving efficiency, reducing environmental impact, and promoting sustainable innovation across various sectors.

2.10 Standards, Tools, Administrative Alternatives, and Opportunities to Sustain MSWM

The International Organization for Standardization (ISO) provides ready-made standards for various categories, which can be used to implement recycling initiatives, life cycle and environmental impact assessments, and sustainable organic waste management. These standards contribute to environmental impact reduction, energy generation, and environmental monitoring. There are administrative alternatives for improving and sustaining MSWM. They help decision-makers adopt appropriate approaches, protect the environment from harmful effects, and develop the administrative process for waste management. The researcher compiled criteria, tools, and management alternatives from the studies reviewed, and Table 2.2 provides a summary of administrative alternatives drawn from the experiences of successful countries and conclusions from various articles.

Table 2.2: Summary of Administrative Alternatives from different resources.

Public Awareness and Education	Waste Reduction Policies	Waste segregation and collection	Recycling programs
Waste Data Management and Analytics Systems	Extended Producer Responsibility	Waste auditing and monitoring	Legal and regulatory frameworks
Voluntary Programs and Certifications	Financial Incentives and Support	Research and development	Waste management planning
Continuous Assessment and Improvement	Green Procurement Policies	Waste-to-energy	International cooperation and best practices
Circular Economy Approach	Stakeholder Engagement	Mobile applications and digital tools	Waste exchange programs
Waste Management Training Certification and Capacity Building	Investment in Waste Management Infrastructure	Cooperation and partnerships with the informal sector	Waste management in national parks and protected areas
Benchmarking and Performance	Innovation and Continuous Research	Public-private partnerships	Waste management in indigenous communities
Green Event Management	Waste Management in Schools and Educational Institutions	Circular economy innovation hubs	International agreements and commitments
Waste Management Education in Healthcare Facilities	Social Enterprises and Job Creation	Waste management innovation funds	Sustainable packaging initiatives
Waste Management Performance Reporting	Green Building Standards	Waste management collaboration platforms	Waste management performance contracts
Waste Management Task Forces	Waste Management in Disaster Response	Waste management innovation challenges	Waste management in construction and demolition

Waste Management in Tourism and Hospitality	Resource Recovery Facilities	Waste management financial instruments	Waste management in e-waste
Waste Management in Agriculture	Waste Management in Remote Areas	Waste management in prisons	LCA

Communication, facilitating waste reduction and reuse processes, and incentives should not be overlooked. These factors are estimated to be more than 90% important in improving waste management (Saitoh et al., 2022). The use of modern mobile phone applications also has an impact on raising awareness and disseminating information directly to individuals.

2.11 Tools to protect the environment in waste management.

Several tools can help decision-makers determine the best ways to protect the environment and manage waste sustainably. One such tool is the use of the LCA methodology, which is used to evaluate the environmental impacts of a product or service throughout its life cycle, from raw material extraction to disposal. Decision-makers also use LCC to evaluate the costs and benefits associated with waste management. Geographic Information System (GIS) technology combines spatial data and analytical tools to support decision-making. Decision Support Systems (DSS) assist decision-makers in complex decision-making processes. Surveys and online platforms can be used to develop waste management policies. Cash-on-delivery schemes contribute to encouraging recycling and the circular economy (Mukherjee et al., 2020).

2.12 Opportunities for improving MSWM and cost outcomes.

Identifying opportunities is a critical management issue for finding optimal solutions to improve waste management. To achieve this, decision-makers must take several important steps. The most important steps are to identify, discover, and evaluate available opportunities. To identify opportunities, it is essential to begin by examining waste to understand its composition and the quantities generated. This will help identify areas that can be exploited to develop plans and implement appropriate initiatives to improve potential environmental outcomes and impacts. This also requires evaluating policies and regulations, exploring gaps and shortcomings, and identifying potential strengths and opportunities that lead to more effective environmental outcomes. Infrastructure analysis and evaluation can guide the identification of shortcomings, help improve environmental performance, and identify innovative ways to address them. Comparing best practices in neighboring countries or countries that have achieved positive results provides valuable opportunities for environmental improvement. The best opportunities can be achieved by engaging stakeholders, whether officials, experts, or community representatives. Discussions with these groups help generate innovative ideas and practical solutions that are closer to reality. With these criteria, tools, and administrative alternatives, the third objective of the research was achieved.

2.13 Environmental Impacts

LCA tool enables monitoring of the environmental impacts of MSWM systems and allows us to see how these impacts change by modifying certain

variables (Deus et al., 2020). It also enables us to assess the overall picture of the entire process, along with its potential to reduce emissions, in conjunction with other methods. In an environmental assessment study, there is a need to understand the environmental impacts based on the latest studies and knowledge.

2.13.1 Choosing Environmental Impacts Categories

Rigon et al. (2019) argue that the selection of an environmental impact category depends on the choice of method used. They state that all relevant environmental impact categories should be included in LCA when studying the impacts of MSW recycling and incineration. When using LCA, priorities should be set to identify the most relevant impact categories. Impact categories are selected based on the needs of the area and prioritize those with the most harmful impact or those that identify the most scarce or vulnerable natural resources. Rigon et al. (2019) found that some studies do not provide any explanation for the decision to select the LCA method.

Environmental impacts are selected based on the need for the type of environmental assessment of MSW and in line with the SDGs associated with waste management.

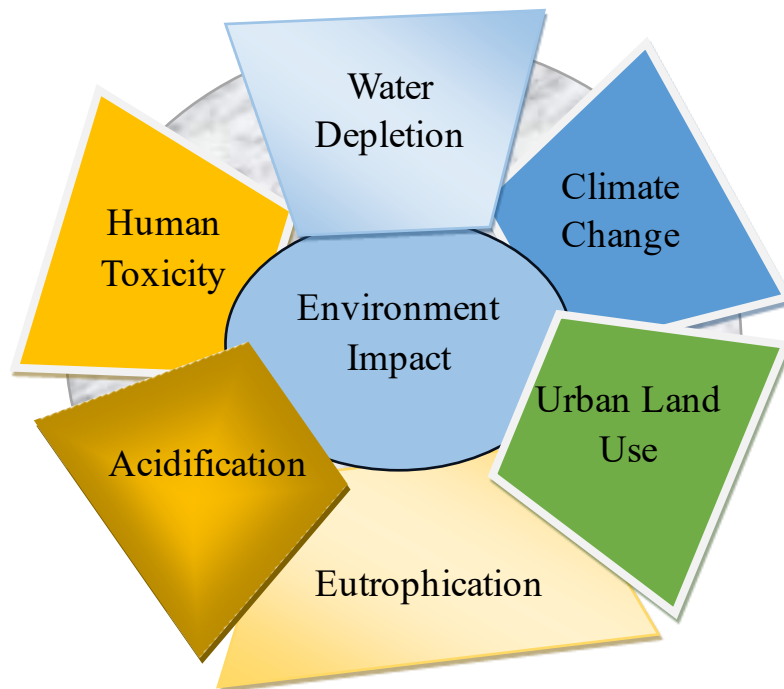


Figure 2.6: Selected Environmental Impacts for assessing the MSWM in Bahrain.

From the above, this study will focus on climate change, water depletion, urban land occupation, acidification, human toxicity, and eutrophication, as illustrated in Figure 2.6. These selections are consistent with the findings of Jolliet et al. (2003).

2.13.2 Criteria for Choosing Scenarios

To arrive at the appropriate scenario, several criteria will be considered when selecting the optimal scenario. These include the Kingdom of Bahrain's tourism importance, the cultural and behavioral issues of residents and expatriates, and the nature and climate of Bahrain. The criteria include ensuring that the proposed scenario has a lower environmental impact than the current system. The proposed scenario must be more rational without

neglecting quality. It must also be socially acceptable, as the level of public awareness significantly influences the choice of system. It must be compatible with future population growth. When selecting a scenario, consideration must be given to whether there is a real need to change Bahrain's current infrastructure, as well as the extent of such change. Adaptation to Bahrain's hot weather and geographical conditions must also be considered.

There are various types of waste treatment technologies. The selection of MSWM technologies depends on the results of a literature review, as well as expert opinion. Factors contributing to the appropriate selection of technology for MSW treatment are technological efficiency, social acceptance, and economic and environmental benefits (Zaman, A. U., 2013).

After analyzing criteria and indicators collected from various literature and reports, the most important technologies used and recommended were extracted based on the experiences of distinguished countries in the field of waste management: composting, incineration, gasification, recycling, anaerobic digestion, and sanitary landfill (Figure 2.7).

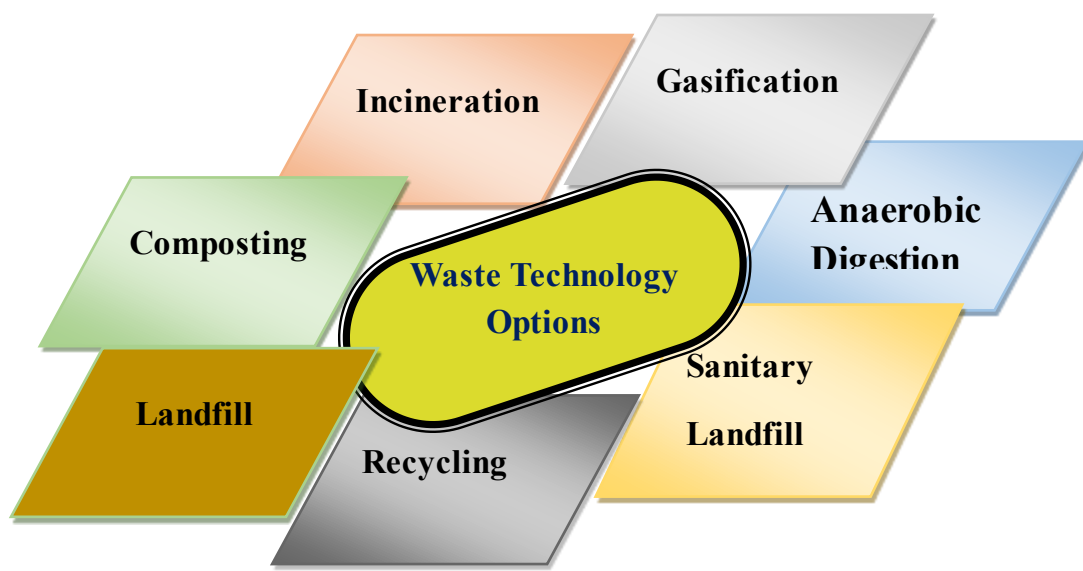


Figure 2.7: MSWM Technology Options (Created by researcher)

2.14 Waste Management Scenarios

This section gives an overview of each scenario that will be tested later using the LCA method by applying the OpenLCA tool.

2.14.1 Landfill

Landfills, the world's most common method of disposing of MSW, occupy land and result in soil and air emissions. A study by Ouedraogo et al. (2021) revealed that landfills contribute significantly to potential global warming, smog formation, acidification, ecotoxicity, over-nutrition, and human health risks. They also pose a risk of water pollution from leaching due to waste decomposition. Furthermore, some carbon compounds are retained in landfills for long periods and therefore do not re-enter the atmosphere as carbon dioxide (CO₂) (European Commission, 2001). MSW landfills produce leachate, which contains various contaminants, including forms of reactive nitrogen (Nr) such as ammonium and nitrate. Additionally, nitrogen, which freely escapes into the leachate, such as ammonia (NH₄), is converted into gaseous emissions. Landfilling poses social and economic challenges, such as land use and pollution, gas recovery costs, difficulty controlling emissions, leachate collection systems, and site longevity.

2.14.2 Anaerobic digestion

AD is an option for waste disposal and produces products with high values of volatile fatty acids (VFA). This process can be improved through the use of diverse microbial communities (Uduak et al., 2023; Anna et al., 2023). Studies indicate that the use of enzymes in anaerobic digestion leads to increased

biomethane production (Nibedita & Md, 2023). Anaerobic digestion contributes to the reduction of GHGs, generates valuable digestate for various applications, and is overall a sustainable solution to waste management (Mariana et al., 2023). Anaerobic digestion represents a promising route for organic waste treatment and a source of renewable energy (biogas) with the potential for use of biofertilizers (BENSON, E., 2022). Waste management specialists have been interested in anaerobic digestion technology because of its potential to produce biogas, which is considered a practical alternative to traditional fossil fuels (Alavi-Borazjani et al., 2020). Anaerobic digestion helps reduce carbon emissions and thus mitigates the effects of GWP (P.M.V. et al., 2023). Anaerobic digestion contributes to the circular economy by recycling nutrients such as phosphorus and nitrogen and enhances waste optimization and sustainable food production (R. Abu et al., 2023). Anaerobic digestion helps reduce the amount of waste while producing renewable energy, thus contributing to the conservation of resources (Havukainen & Dace, 2023).

2.14.3 Incineration

During waste incineration, harmful airborne pollutants such as sulfur dioxide, nitrogen oxides, hydrochloric acid, fine particulate matter, and dioxin are emitted. It also emits both carbon dioxide and nitrogen dioxide, which contribute to GWP. In the event of energy recovery, it can replace fossil fuels and thus avoid the resulting gas emissions. Metals can be recovered for recycling from bottom ash, which can be reused as secondary aggregate (European Commission, 2001).

2.14.4 Gasification

The gasification method, which is an alternative to MSW disposal, converts waste into energy but leads to air and soil emissions (Ouedraogo et al., 2021). The effects of gasification of MSW can be attributed to the dumping of its solid waste (Ouedraogo et al., 2021).

2.14.5 Composting

Composting is defined as the conversion of organic waste into a humus-rich compost with the help of microbes in specific vegetation (Suthar et al., 2012). There are many types of fertilization, including aerobic/anaerobic, organic fertilization, and fertilization based on microorganisms, which is fast and effective. Composting is also used to reduce waste and benefit from it in vegetable cultivation, as is the case in Ecuador (Gavilanes-Teran et al., 2016). There are many types of active microorganisms, estimated at 2000 species, for example, *Lactobacillus*, *Streptomyces*, *Rhodobacter*, etc., and these can decompose lignocellulosic waste and contribute to the acceleration of the composting rate (Muttalib et al., 2016). In the composting process, methane gas production from the decomposition of organic waste in landfills is avoided.

2.14.6 Recycling

The recycling process saves energy and reduces emissions of GHGs and other pollutants. This process contributes to extending the reserves of limited resources, such as minerals and others, and contributes to the sustainability of these resources. It contributes to avoiding the effects associated with the extraction of raw materials (European Commission, 2001). The results of the study by Wang et al. (2020) indicated reductions in GWP in Nottingham

through LCA due to improvements in waste management, use and treatment, material recycling, and waste prevention. Waste sorting and reuse increase the savings of primary resources and energy, in addition to reducing the burden on the environment. Gala et al. (2015) stress that when the recycling market is in its infancy, its implementation is commendable, despite the initial cost, and patience and perseverance are required. In the 27 EU countries, 39% was recycled in 2010 (Eurostat, 2014), and in 2020 the recycling rate was around 48%. Around 40% of the biological waste generated from MSW ends up in landfills (European Commission, 2009). Construction and demolition waste (CDW) in Nanjing, China, was recycled at a rate of approximately 90%. Approximately 1.8 million cubic meters of land area resources were saved, equivalent to approximately 3 million tons of construction waste. This resulted in savings of approximately 1.8 million cubic meters of land area resources and approximately US\$13,962,790 (Wu, W. et al., 2022).

2.14.7 Sanitary Landfill

In a sanitary landfill, waste is isolated from the environment until it decomposes, and its decomposition is used to capture gases. This is important given the environmental and health risks caused by waste facilities (Shafie et al., 2018). LCA helps assess the environmental and health impact of a sanitary landfill and provides a judgment on the overall risk. It contributes to addressing environmental degradation issues and is considered an alternative to the indiscriminate disposal of solid waste. Wang et al. (2021) studied a landfill in the United States to reduce waste volume and control the collection of emitted gases using LCA. They found that each area differs in its conditions and waste types, so each area should be studied separately.

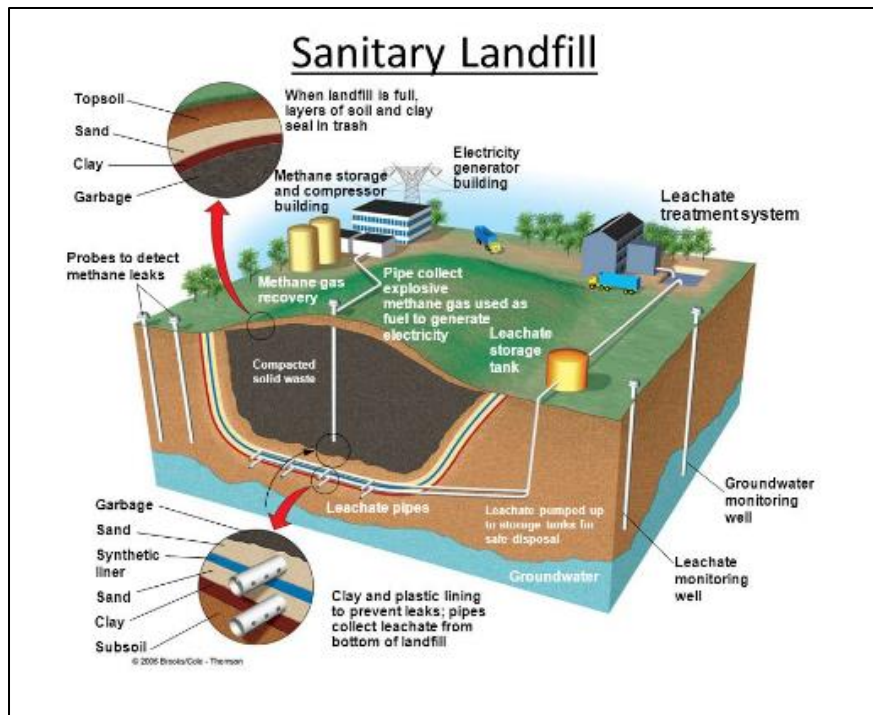


Figure 2.8: Sanitary landfill example.

(Source: <https://www.pinterest.com/pin/245375879685146353/>)

Their study indicated that rapidly decomposing materials, such as food waste, contribute to increased methane emissions, while gas collection efficiency decreases in humid areas, regardless of landfill size. Sanitary landfills are the most widely used method for waste treatment due to their ease of implementation (Das et al., 2019). Sanitary landfills, as described by the U.S. Environmental Protection Agency (USEPA, 2016), consist of four layers (Figure 2.8). These layers are intended to capture landfill gases and prevent the release of gases that are harmful to the environment and humans. Over time, it has been discovered that conventional landfills emit large amounts of nitrous oxide (N_2O), methane (CH_4), and hazardous heavy metals (Das et al., 2019).

2.15 Current Status of MSWM in Bahrain

Waste collection worldwide ranges from 48% in low-income countries to around 90% in Europe, and in Bahrain, waste collection is 100% (World Bank, 2025). Data on MSW was collected from the Bahrain e-portal for twenty calendar years, between 2000 and 2020. These quantities must be known to account for changes in waste flow and composition over time. The Ecoinvent database was consulted for unavailable data.

There are two cleaning companies in Bahrain, each responsible for two governorates. Urbaser (Northern and Southern) and GCCC (Muharraq and the Capital). Urbaser has been managing the landfill since October 2019 with a three-year contract worth BD 4.8 million. A scale is installed at the landfill gate to calculate the weight of the truck and the waste. The GCCC company won the construction waste management tender, reducing the amount of general waste by 30%. The collection fees for trucks arriving at the landfill have now changed from BD 0.250 to BD 2.5 per ton. A fee of BD 7 per trailer and BD 0.080 per ton is charged to each construction waste trailer entering the landfill. GCCC pays the government BD 0.080 per ton, in addition to land rent and a 10% factory tax (per ton weight). Household waste is collected daily in Bahrain, while in the UK, it is collected twice weekly due to climatic conditions.

Knowing the composition of MSW helps decision-makers make informed decisions. Knowing and analyzing waste composition also helps determine its environmental impacts. It is essential to determine the proportion of different waste elements or materials in the waste stream using waste composition, also known as waste sorting. The Center for Waste Management "Estidama" issues

a periodic report on the increasing daily household waste produced in the Kingdom of Bahrain, as shown in Figure 2.9. Obtaining preliminary information on the quantity of waste by type and the precise details of its MSW content contributes to developing a clear vision on how to reduce it to preserve the environment and resources, especially with the annual increase in its quantities (MMAA, 2018).

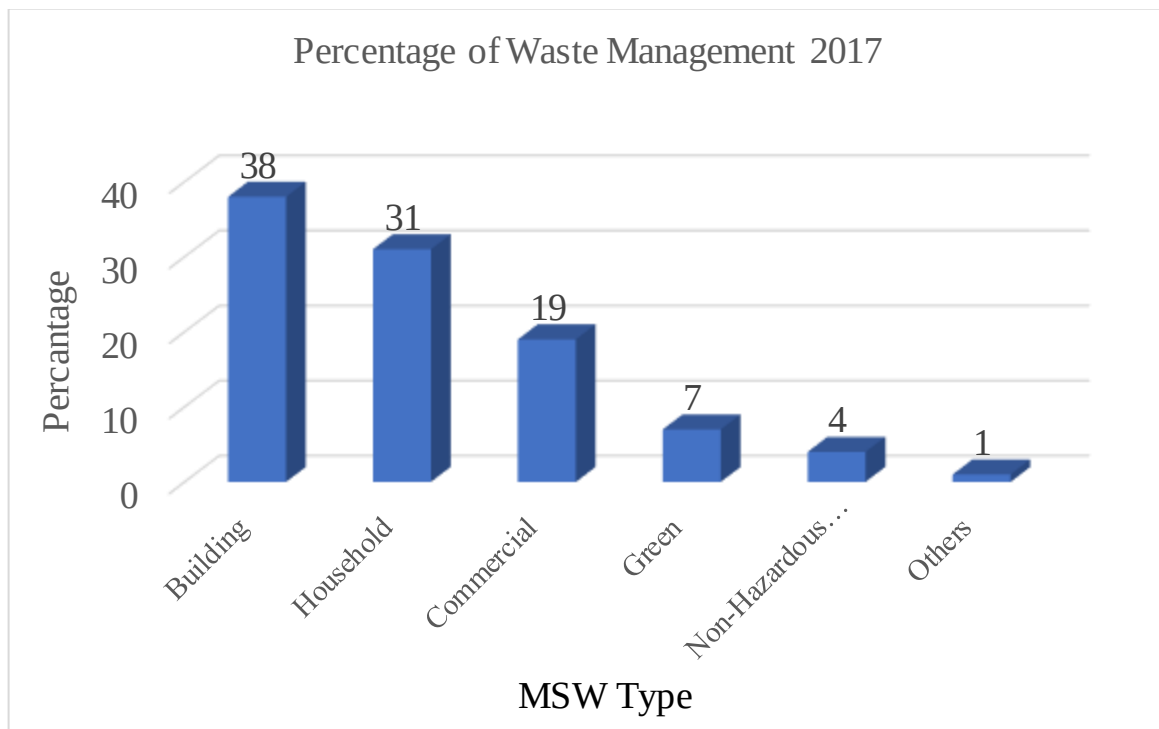


Figure 2.9: Bahrain household waste percentages (MMAA, 2018).

Table 2.3 presents the daily composition of waste types in Bahrain, highlighting the proportions of various waste categories based on data from Estidama_bh (2020). Building waste constitutes the largest share at 38%, followed by household waste at 31%, reflecting the significant contribution of residential areas to the overall waste stream. Commercial waste accounts for 19%, indicating the role of business activities in daily waste generation. Green waste, which includes plant and garden residues, makes up 7%, while non-

hazardous industrial waste contributes 4%. The remaining 1% is categorized as "Others," encompassing miscellaneous or unclassified waste types. This distribution emphasizes the dominance of construction and domestic sources in Bahrain's MSW profile.

Table 2.3: Types of waste produced daily and their proportions. Source (Estidama_bh, 2020)

Type of Waste	Percentage
Building	38
Household	31
Commercial	19
Green	7
Non-Hazardous Industrial	4
Others	1
Total	100

Table 2.4 shows the annual composition of household waste in Bahrain, based on data from Estidama_bh (2020). Food waste represents the largest portion at 35.2%, followed by plastic at 30.1%, indicating high levels of organic and packaging waste. Paper and cardboard account for 11.6%, while smaller proportions are observed for textiles (4.1%), glass (3.3%), metal (3.2%), and other materials (9.7%). Organic waste, excluding food, makes up 2.8% of the total.

Table 2.4: Percentages of household waste components annually in the Kingdom of Bahrain. Source: (Estidama_bh, 2020)

Type of Waste	Percentage
Organic	2.8
Food	35.2
Others	9.7
Metal	3.2
Glass	3.3
Plastic	30.1
Textile	4.1
Paper and cartoon	11.6
Total	100

Figure 2.10 illustrates the average daily waste streams generated in Bahrain, as reported by Estidama_bh (2020). The figure provides a visual breakdown of the different waste types produced on a daily basis, highlighting the relative quantities of each stream. It emphasizes the predominance of certain waste categories—such as construction, household, and commercial waste—within the total daily generation. This representation aids in understanding the scale and composition of Bahrain’s daily waste output, which is essential for planning effective waste management strategies.



Figure 2.10: Average Daily Waste Streams Generated Source: (Estidama_bh, 2020)

Table 2.5: Bahrain's annual home garbage creation rate for the previous 20 years, from 2000 to 2020 (Bahrain Open Data Portal, 2025)

Domestic Waste	
YEAR	TONS
2000	234187
2001	274237
2002	279295
2003	293111

2004	323990
2005	306203
2006	312983
2007	287205
2008	380871
2009	402241
2010	457335
2011	430836
2012	444801
2013	463860
2014	465079
2015	469489
2016	507350
2017	559053
2018	563915
2019	566125
2020	601296

Table 2.5 presents the annual generation of domestic waste in Bahrain over 20 years, from 2000 to 2020, based on data from the Bahrain Open Data Portal (2025). The data shows a clear upward trend in household waste production, rising from 234,187 tons in 2000 to 601,296 tons in 2020. Despite some fluctuations in the early 2000s, the overall trajectory indicates significant

growth, particularly after 2008, reflecting increased population, urbanization, and consumption patterns in the Kingdom.

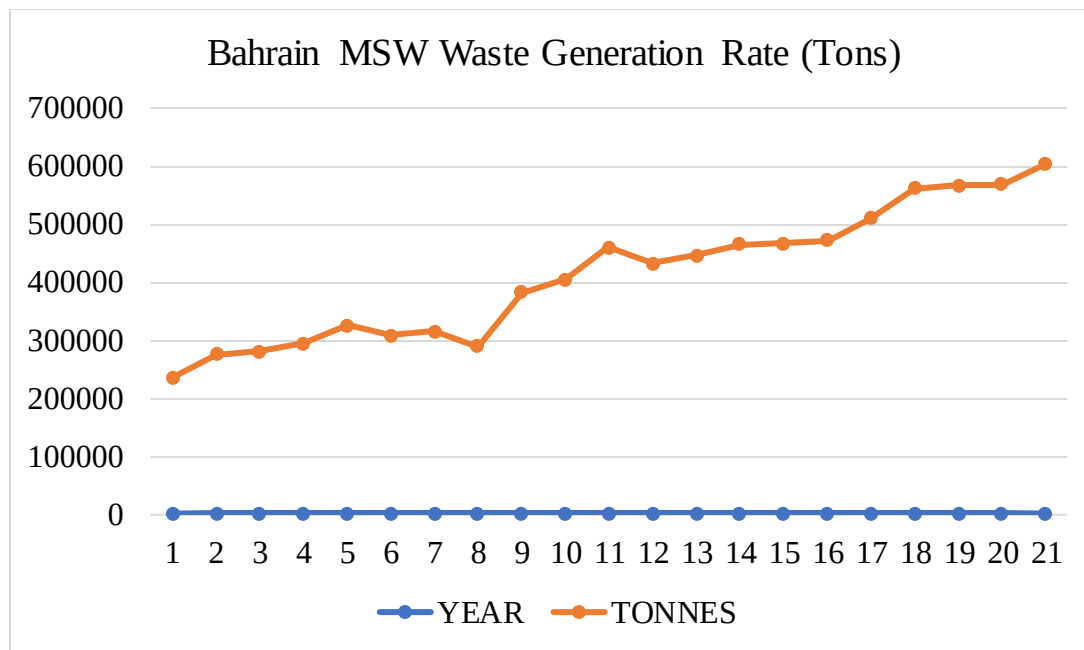


Figure 2.11: MSW generation rate per year for the previous 20 years.

Source: (Bahrain Open Data Portal, 2025), (Figure created by the researcher)

Figure 2.11 illustrates the municipal solid waste (MSW) generation rate in Bahrain over the past 20 years, based on data from the Bahrain Open Data Portal (2025) and compiled by the researcher. The figure highlights a steady and notable increase in MSW generation, reflecting the country's rapid urban growth, rising population, and evolving consumption patterns. This trend underscores the growing pressure on Bahrain's waste management systems and the urgent need for sustainable waste reduction strategies.

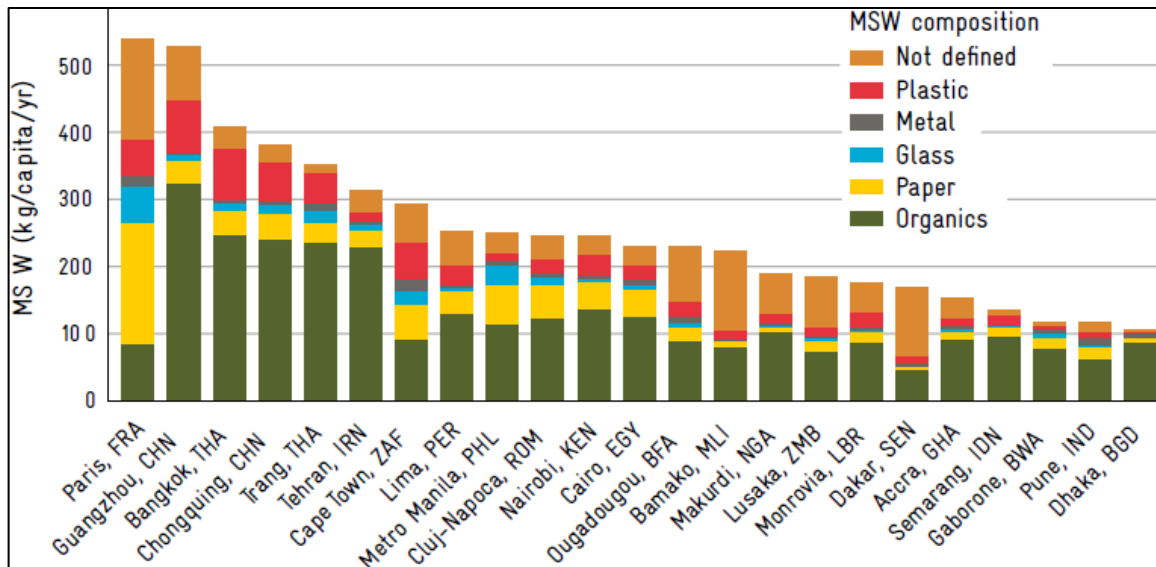


Figure 2.12: MSW composition per capita (kg/capita/year) in different global cities.

Source: (Mutz et al, 2017)

According to a study by Mutz et al. (2017), Figure 2.12 displays the rates of local solid waste generation per capita (kg/person/year) in various cities worldwide to compare the rate of local solid waste generation in Bahrain with other cities worldwide.

According to Table 2.6, Bahrain generates 1358 kg of MSW per capita annually, whereas it is only 530 kg/capita/year in Paris and considerably lower in other cities, as shown in Figure 2.12. This shows that the rate of MSW generation is significant in a small nation like Bahrain, stressing how urgently a sustainable waste management solution is needed as opposed to simply depositing it in a landfill where it would eventually outlive its usefulness.

According to Table 2.6, the Kingdom of Bahrain produces 1610 tons/day of household waste of which 660 tons a day is accounted for by OHW.

Table 2.6: An overview of Bahrain's garbage statistics. (Source: Supreme Council for Environment.com)

Bahrain MSW Statistics (2021)			
Type	ton/year	kg/day	ton/day
Total Bahrain MSW to landfill	2,026,631	5,552,414	5552.4
Total Bahrain HW (29% of MSW)	587,723	1610200	1610.2
Total Bahrain OHW (41% of HW)	240,966	660181	660.2
Population	People		
Bahrain Population (2017)	1,492,584		
Generation Rate	kg/capita/ day	ton/capita/year	
Bahrain MSW generation rate	3.720	1.358	
Bahrain HW generation rate	1.079	0.394	
Bahrain OHW generation rate	0.442	0.161	

2.16 Summary of Chapter 2

This chapter addressed the first, third, and fourth objectives through a comprehensive review of theories and literature. It examined the global evolution of MSWM practices and LCA applications, identifying key trends, best practices, and technological solutions. It also reviewed administrative tools and policy instruments that contribute to sustainable waste governance, thus directly supporting objective 3. Additionally, it explored global innovations in MSWM technologies, offering a knowledge base for proposing context-specific options aligned with objective 4.

Chapter 3 Methods and Procedures

3. Introduction

This chapter discusses the methodologies, steps, and procedures used throughout the research phases. It includes LCA methodology and details its implementation in assessing the status of MSWM in the Kingdom of Bahrain. The selection of OpenLCA software and its implementation are then explained. This chapter explores the relationships between LCA and various related topics. The chapter discusses the LCC method. It then discusses the process of measuring public opinion and exploring community knowledge, attitudes, and practices, followed by interviews with experts. The procedures and tools used to achieve the research objectives are also discussed.

3.1 About Bahrain

Bahrain is an archipelago consisting of 33 islands (Knoema, 2021). Its location and map are shown in Figure 3.1. Bahrain, with its capital Manama, is in the Arabian Gulf and Western Asia. The total area of 8,269 square kilometers, the land area is 786.5 km². The Kingdom of Bahrain is divided into four governorates: the Capital, Muharraq, Northern, and Southern. The official language is Arabic, while English is used as the official language in the business sector. The official religion is Islam, practiced by most Muslims. Bahrain is an open country that embraces various religions. Oil and natural gas are among Bahrain's major natural resources. According to Knoema (2021), the population of Bahrain is 1,504,365, and it will reach 2.128 million in 2030.



Figure 3.1: The Kingdom of Bahrain Location (Source: <https://geomasterglobal.wordpress.co>)

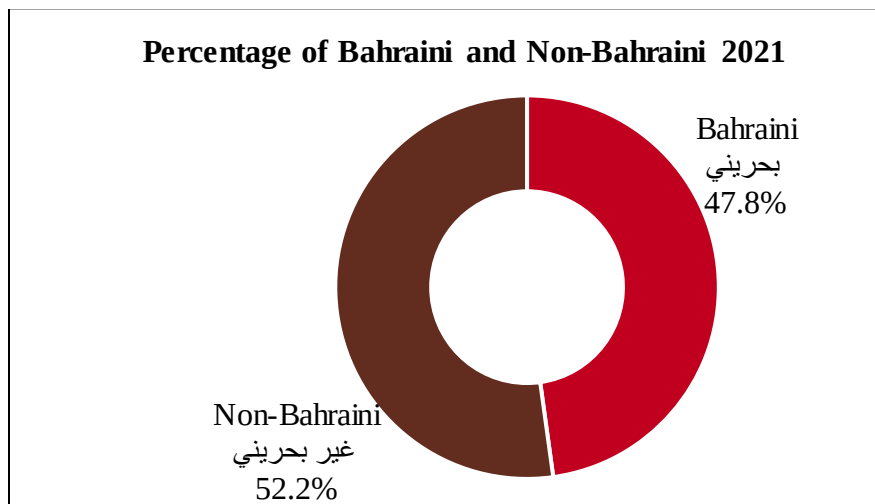


Figure 3.2: Content of Bahrain Demographics (Source: IeGA, 2021)

Its population consists of 47.8% Bahrainis and 52.2% non-Bahrainis, as shown in Figure 3.2. Bahrain has a dry climate. The average annual rainfall is small, reaching 70.8 mm, and it is irregular. The summer period is considered from June to September, and the winter period is considered from December for four months, separated by two in-between periods as shown in Figure 3.3. Bahrain's summer is very hot, and its winter is mild. From December to February, the average winter temperature is 17°C. June through August sees an average summer temperature of 38°C. The average monthly humidity is usually as high as 67 percent, and the daily average ranges from 78 percent to 88 percent (MOTT, 2023).

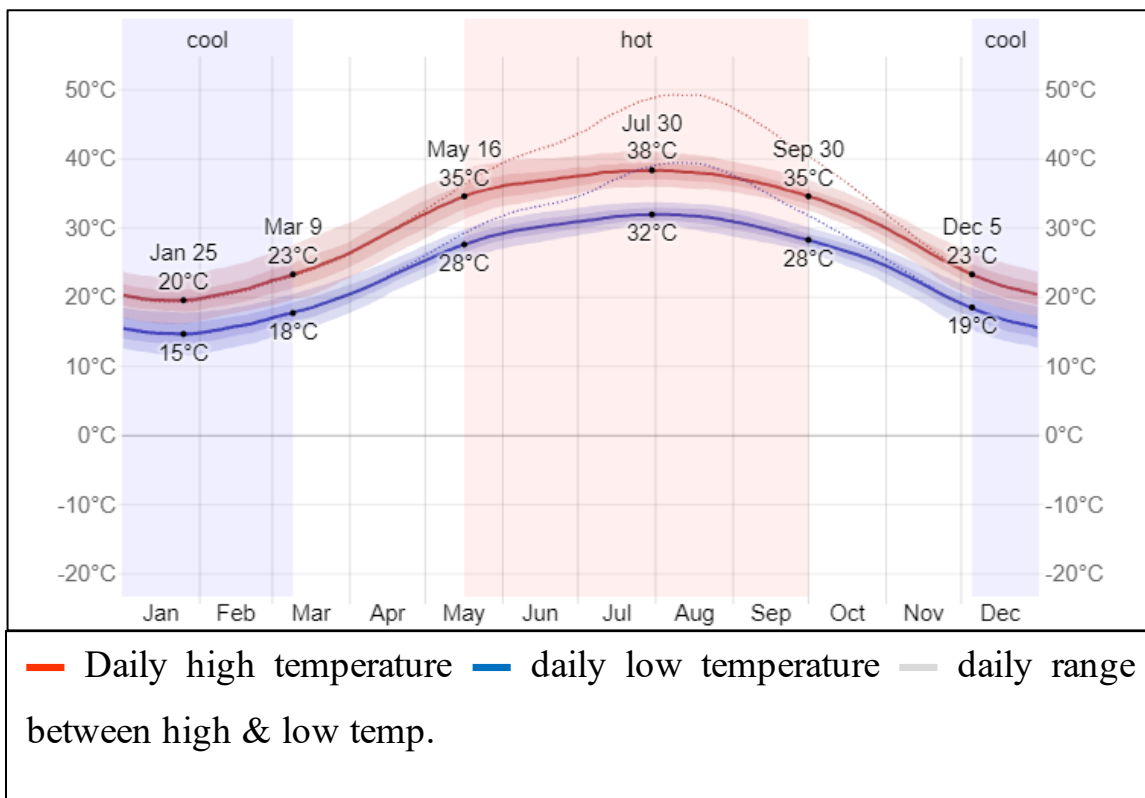


Figure 3.3 : Daily temperatures for Bahrain in 2023 -Source: WeatherSpark (2023)

Despite the Kingdom of Bahrain's prosperity, its dependence on oil and gas and limited land resources poses concerns about its sustainable development. Since the Kingdom of Bahrain is an island nation, rising sea levels brought on by climate change pose major risks to the environment and sustainable development (Al Sabbagh, 2012).

3.1.1 MSWM in Bahrain

Bahrain's Vision 2030 emphasizes achieving sustainable development goals and ensuring a prosperous life for every Bahraini (Bahrain.bh, 2025). Despite its limited land area, Bahrain produces large quantities of waste. Decision-makers are striving to address the challenges facing waste management as the rate of waste generation increases (Zafar, 2016). Concerns are growing that this increasing volume will lead to a decrease in landfill capacity, and current practices are considered unacceptable due to the environmental impacts of waste and its increasing problems (Al-Ansari, 2012). Despite numerous newspaper announcements and statements regarding plans to convert waste to energy, these have not yet seen the light of day. There is little published information and data on waste management; Table 3.1 represents what has been collected on waste in Bahrain.

Table 3.1: The Publicly Available Literature on Waste Management in Bahrain.

Title	Author /Editor/Contributor	Publish year
Domestic waste and methods to benefit from it. State of	Al Madani, I, and Abu Shosha, M.	1992

Bahrain. Al Qabas Printing Press (in Arabic)		
Bahrain's Initial communications to the United Nations Framework Convention on Climate Change. Volume 1: Main Summary Report.	Kingdom of Bahrain General Commission for the Protection of Marine Resources, Environment & Wildlife. Kingdom of Bahrain. Enz Zahwa Al Kawari.	March, 2005
Bahrain National Assessment Report on Implementation of The Mauritius Strategy (MSI) of The Barbados Programme of Action (BPOA)	The Public Commission for Protection of Marine Resources, the Environment and Wildlife of the Kingdom of Bahrain	November, 2009
Bahrain's Second National Communication Under the United Nations Framework Convention on Climate Change, Kingdom of Bahrain Public Commission for the Protection of Marine Resources, Environment and Wildlife. Bahrain Second National Communication Under the United Nations	Dr. Bill Dougherty, Dr. Mahmoud Abdulla Medany, Dr. Sabah Saleh Al Jenaïd, Dr. Mohd Sulaiman Abido, Dr. Hamida Mohamed Klai, Professor Waleed K Al-Zubari, Prof. Ibrahim Abdel Gelil, Dr. Randah Hamadeh, Professor Waheeb Essa Alnaser.	January, 2012

Framework Convention on Climate Change		
MSWM systems in the Kingdom of Bahrain	Mohammed Saleh Al. Ansari	April, 2012
Resource Management Performance in Bahrain: A Systematic Analysis of Municipal Waste Management, Secondary Material Flows and Organizational Aspects.	Maram K Al Sabbagh, Costas A Velis, David C Wilson, and Christopher R Cheeseman	May, 2012
Exploring the Opportunity for Organic Household Waste (OHW) Management Technology Options: An Empirical Investigation for Muharraq Governorate	Dr. Sumaya Yosuf Abbas.	January, 2019

An international comparative analysis shows that recycling and material recovery rates in Bahrain represent 8% by weight of household waste, while the amount of waste generated is relatively high, at 1.1 kg per capita (Al Sabbagh, 2012).

3.1.2 Current MSWM Approach in Bahrain

Waste is monitored through a center called “Estidama Center”, which contributes to promoting sustainability and tracking household waste in the Kingdom, using the latest internationally approved systems. In Bahrain, a new

hygiene law was passed, representing a significant qualitative shift in highlighting the civilized image of the Kingdom of Bahrain. This law addresses many previously absent points and loopholes and addresses numerous negative environmental phenomena.

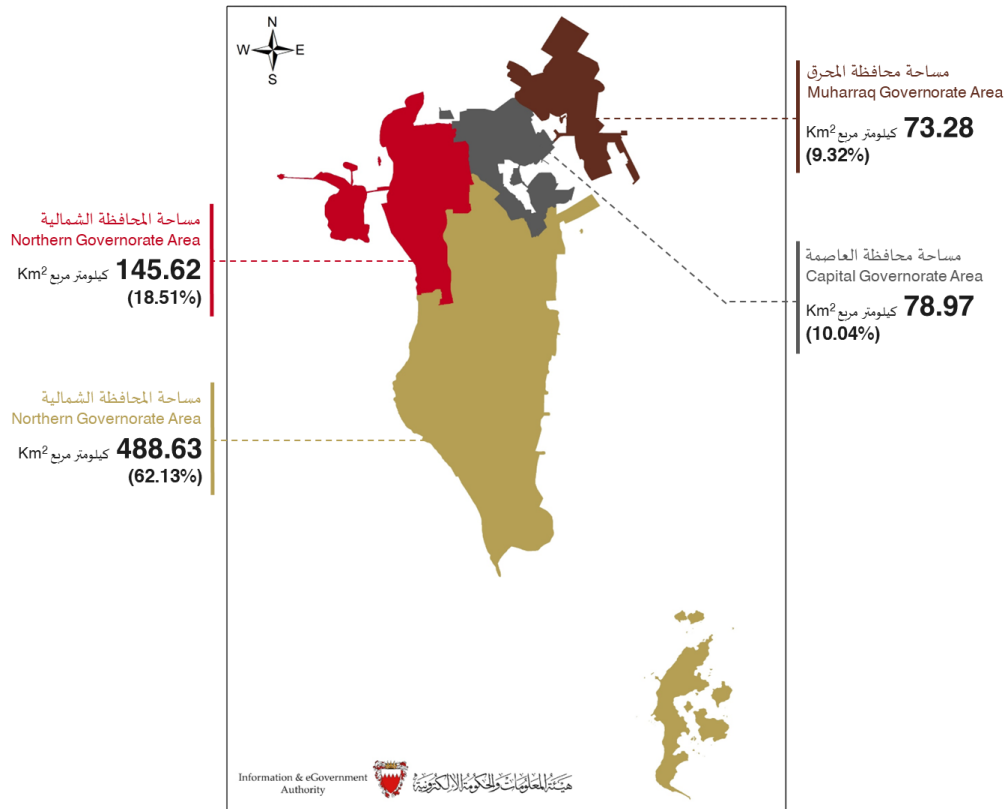


Figure 3.4: Bahrain Map with all Municipalities (Source: IeGA, 2021).

Figure 3.4 displays a map of Bahrain highlighting all of its municipalities, based on data from IeGA (2021). The map provides a clear geographical overview of administrative divisions across the Kingdom and serves as a useful reference for understanding the spatial distribution of governance and service areas, including MSWM responsibilities.

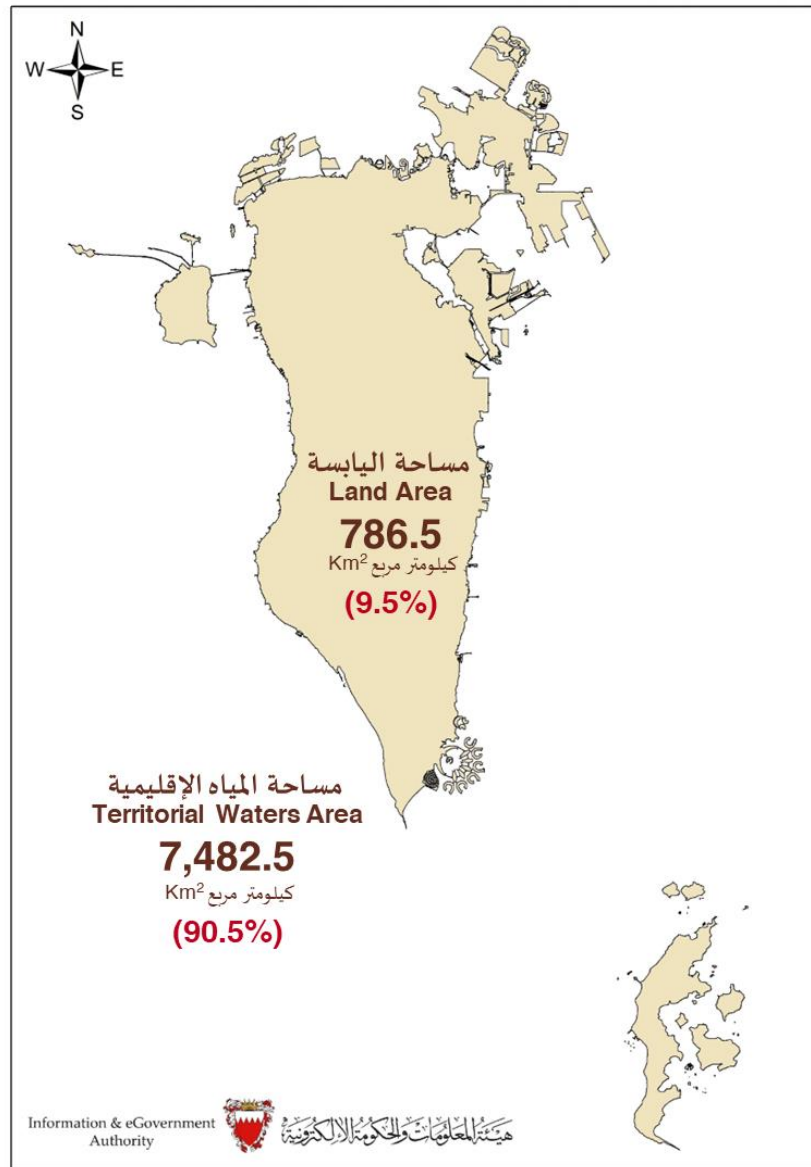


Figure 3.5: Area of the Kingdom of Bahrain – 2021 (Source: IeGA, 2021)

Figure 3.5 presents the total land area of the Kingdom of Bahrain as of 2021, sourced from IeGA (2021). The figure offers a detailed spatial representation of the country's geographical extent, which is essential for planning and

managing land use, infrastructure development, and environmental services such as MSWM across different regions.

Table 3.2: The population, area, and population density of four governorates in Bahrain. (Source: IeGA, 2021)

Governorate	Area (km ²)	Population Estimate (2021)	Population Density per km ²
Capital	78.97	538,965	6824
Muharraq	73.28	263,430	3594
Northern	145.62	396,779	2724
Southern	488.63	305,191	624
Total	786.5	1,504,365	1912

Table 3.2 provides data on the area, population, and population density of Bahrain's four governorates based on 2021 estimates from IeGA. The Capital Governorate is the most densely populated, with 6,824 people per km², despite having a smaller area (78.97 km²). In contrast, the Southern Governorate, the largest (488.63 km²), has the lowest population density at 624 people per km². Muharraq and Northern governorates have moderate densities of 3,594 and 2,724 people per km², respectively. The total population across all governorates is 1,504,365, spread over 786.5 km². The Askar Non-Hazardous Waste Landfill is in the Southern Governorate, as shown in Figure 3.6, with an area of more than 700 acres (2.83 km²) (Zafar, S., 2023).



Figure 3.6: Askar landfill location and proposed area for landfill extension.

Source : https://www.frontiersin.org/files/Articles/1302711/fenvs-11-1302711-HTML/image_m/fenvs-11-1302711-g002.jpg

It is a large pit used for waste disposal/burial; its depth is about 10 meters. This site has been in operation since February 1986. The previous landfill was in Al Buhair area but was closed due to its proximity to residential areas, and then Al Buhair landfill was closed in September 1987. Askar landfill was expected to reach the end of its lifespan in 2016, but waste is still being dumped in it. (Khalil, 2017).

3.2 Proposed Framework

Waste is viewed as a finite resource awaiting economic recovery. Through proper management and the selection of a treatment method, the value of waste can be recovered (Inghels, D. A. M., 2016). The method chosen should consider the impact of reducing greenhouse gas emissions.

Figure 3.7 presents the SELECT model, a multidimensional framework for assessing MSWM across six interconnected dimensions: Social, Environmental, Legislative, Energy, Cost-effectiveness, and Technology.

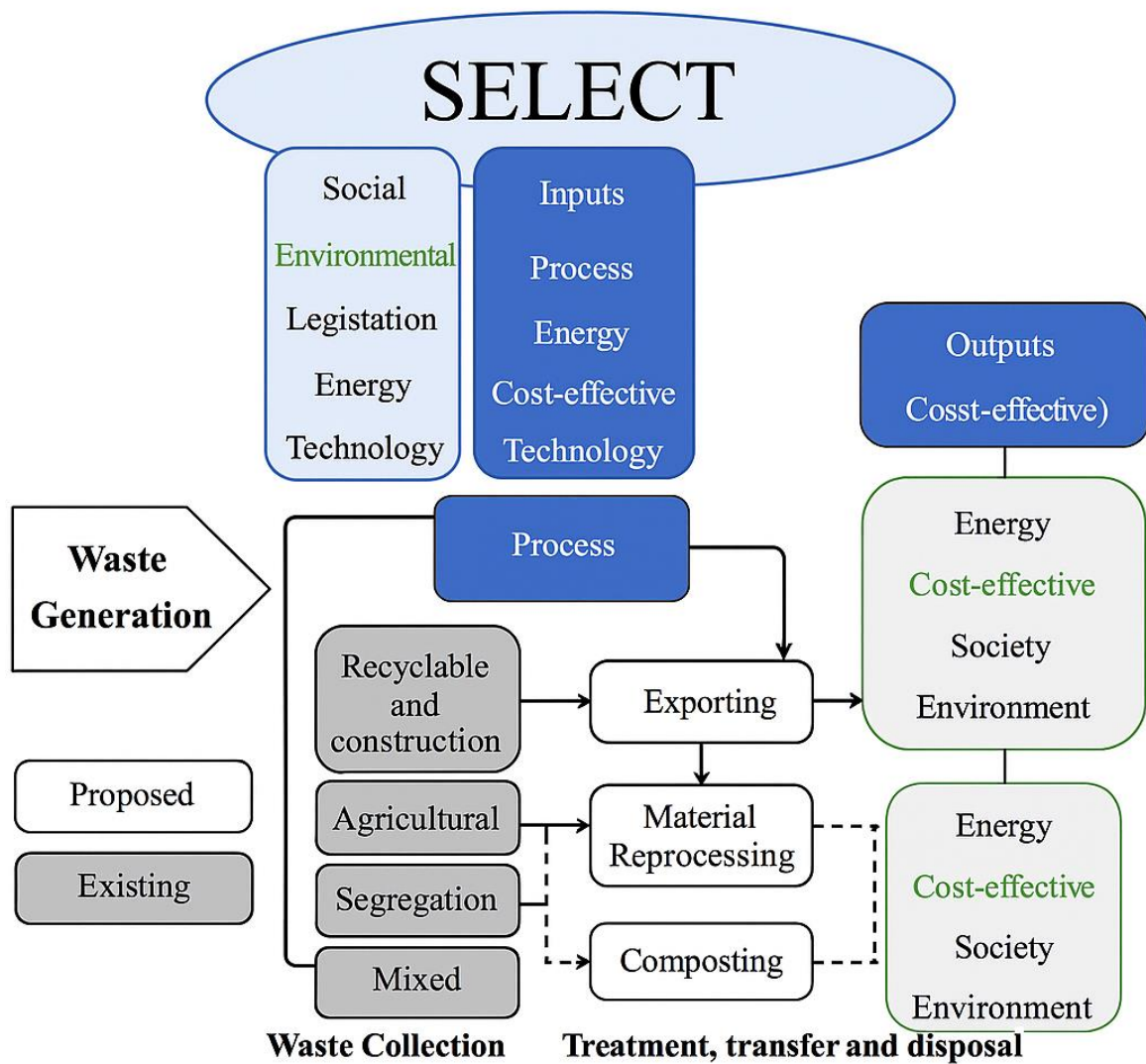


Figure 3.7: Integrated conceptual framework of municipal solid waste flow incorporating the SELECT model for sustainability evaluation across system stages.

This model, which integrated across all stages of waste flow—from generation to disposal—ensures that sustainability is considered at every stage. The model evaluates inputs, transportation mechanisms, and treatment options like composting and waste-to-energy based on their social, environmental, legal, and economic impacts. SELECT is based on system thinking, supports evidence-based decision-making, enhances sustainability outcomes, and transforms MSWM into a holistic, integrated process.

3.3 Applying tools in the proposed model

This research uses several methodologies, research tools, and procedural steps that are summarized here as in Figure 3.8.

LCA is one of the most common methods in the field of environmental impact assessment in the subject of MSW to estimate emissions and assess environmental impacts (UNEP, 2024). The benefits of LCA are that it helps decision-makers in strategic planning in the process of improving the environmental performance of products and processes at different stages of the life cycle.

The tools used in the research are: OpenLCA, a quantitative questionnaire, qualitative interviews, and LCC. Information extraction from the description of the waste management situation in the Kingdom of Bahrain will be based on articles published either in previous research or through reports. The electronic data platform in Bahrain will be used.

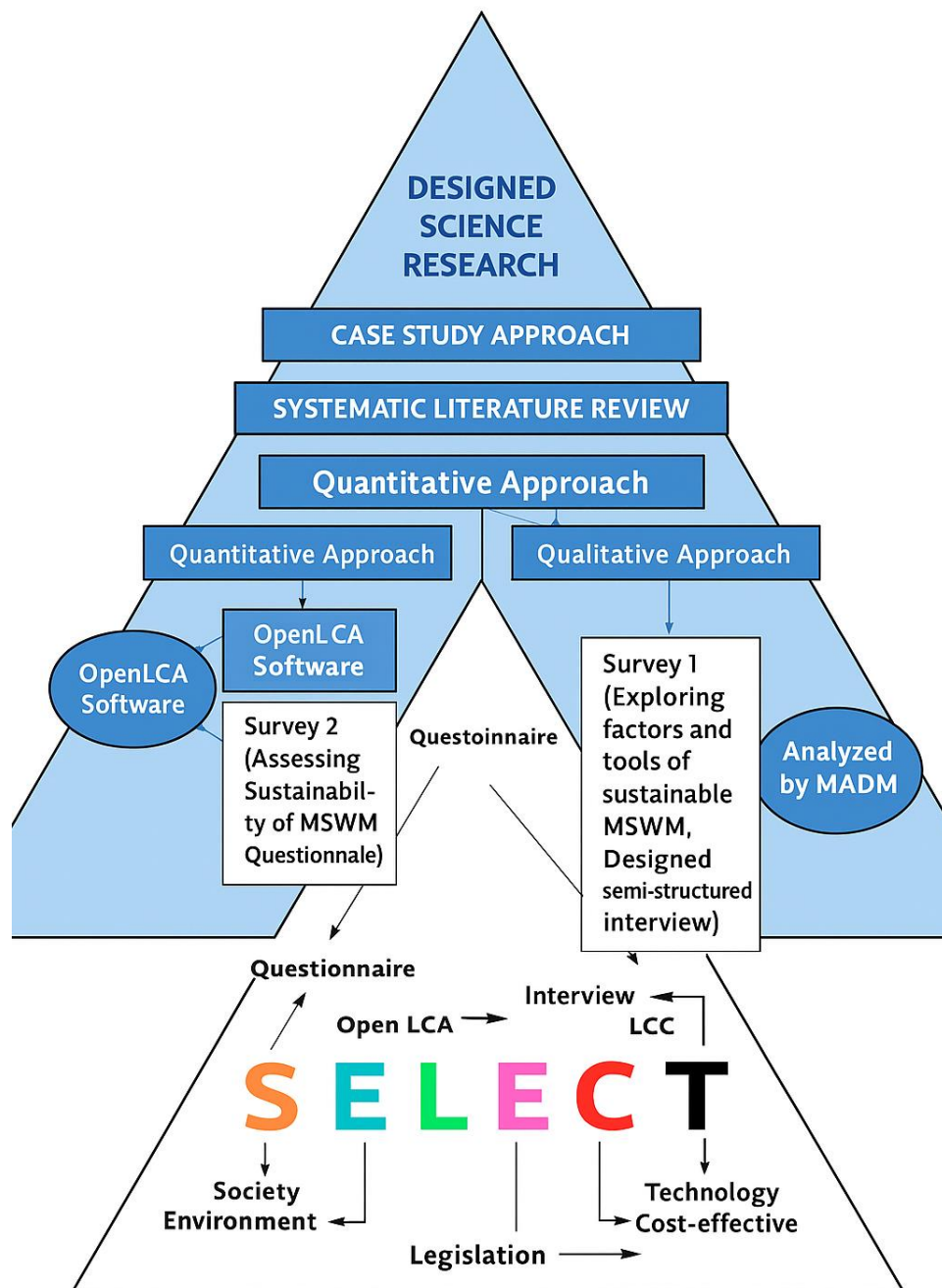


Figure 3.8: A summary of the research methodologies and their interrelation.

3.4 OpenLCA software

OpenLCA is an open-source LCA software developed by Green Delta and includes databases (Ferronato et al., 2020). Students, professors, and academic researchers at schools and universities are licensed to download the database for academic purposes (Nexus, 2022). It is considered more flexible and powerful than commercial LCA software, as processes can have major products on either the output or input side, with the input being waste processing. Product systems display a typical life cycle and can be modified, and there is no supply chain "plugged" into a database. The primary purpose of OpenLCA was to analyze the environmental life cycle of a product, which has subsequently evolved into an economic life cycle (OpenLCA.org, 2022). Paul et al. (2024) used the LCA method to determine the environmental impact of an end-of-life (EOL) treatment of one ton/day using OpenLCA. OpenLCA was chosen for this research due to its free access and user-friendly interface. The latest version of the software can be downloaded for free from its website, www.openlca.org, and databases can be added via the OpenLCA Nexus platform, which contains many databases such as Ecoinvent. Life cycle modeling in OpenLCA consists of four elements: flows, processes, product systems, and projects (Rathnayake, M., 2020).

Ecoinvent is a database released by the Ecoinvent Center in September 2020. It contains 900 new datasets, 1,000 updated datasets, and 100 new products. In total, there are 19,000 datasets for each system model. It is characterized by its developmental improvement (Ciroth & Salwa, 2020). This database system provides models such as rules using different customizations, end-of-life modeling, and process linking. Ecoinvent is an organization that provides high-quality global data for LCA based in Zurich, Switzerland. It provides

data freely and affordably to researchers, NGOs, policymakers, and academia. Researchers are licensed to apply for the database free of charge. This database contains thousands of processes, such as production, processing, management, and others. Using the Ecoinvent database, with its readily available data, helps support scenarios where local data are not available.

OpenLCA Nexus is an online data repository for LCA, available free of charge on the website, subject to registration. It is compatible with the OpenLCA database for the free and open source OpenLCA software (OpenLCA Nexus, 2023). In OpenLCA, generally, the platform provides and allows you to gather Inventory Data (LCI – Life Cycle Inventory). The core data collected and used in LCA studies are raw materials, energy, water, emissions to air, water, soil, and waste generation, for process data (e.g., manufacturing, transportation, waste treatment). These data are typically gathered from LCI databases (Ecoinvent). Also, Environmental Impact Data like Impact categories (e.g., Climate Change, Acidification, Human Toxicity), and Impact assessment results using methods like ReCiPe, IPCC, TRACI, and EF Method (Environmental Footprint). OpenLCA can integrate costs used in LCC.

3.5 Perform LCA in MSWM with OpenLCA

LCA procedures are divided into four phases:

Phase 1: Defining the objective and scope, unit of use, system constraints, system boundaries, level of detail, and users of the results. LCA is determined based on the subject and purpose of the study. The breadth and depth of LCA also depend on the specific objective.

Phase 2: Data inventory and identification of inputs and outputs, also known as life cycle inventory analysis (LCI), is the phase where the data required for the study are identified and analyzed according to the objectives.

Phase 3: The purpose of this phase is to provide the necessary support for LCA and to understand its environmental significance. This phase is known as life cycle impact assessment (LCIA).

Phase 4: This is the final phase, where the analysis results are summarized, conclusions and recommendations are discussed, and decisions are made based on what was previously determined.

OpenLCA is an open-source software used for conducting LCA, enabling users to model and analyze the environmental impacts of products, processes, or systems across their entire life cycle.

3.5.1 Phase 1: Goal and Scope, Limitations of the System

To apply LCA, the following steps, as shown in Table 3.3, should be answered and completed.

Table 3.3: Steps of applying LCA, phase 1.

Goal /purpose	• Goal: Assessing the environmental effects of the current situation of MSWM in Bahrain to find out the implications of the current handling and decision-making of MSW, and to find the best scenario to make it environmentally friendly. • Target group: To help decision makers in the government to take the necessary decisions to improve the environmental
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	situation and choose the best methods and tools for waste management.
Application	The basis for decisions on selecting the MSWM system.
Functional unit	One unit of MSW of household is one ton per day of MSW generated.
System boundaries	• The impact of waste in the Kingdom of Bahrain, which is collected from homes and dumped in the Askar landfill. • All processes contributing significantly to the life cycle impact are considered (collecting, transportation, and treatment).
Scope	• Treatment (solution) to be assessed. • Assessment of the current service. • Assessing the impact of collecting in the landfill. • Testing seven technologies and finding the best.
Inventory	• Finding the data available and required. • Qualifying the collected data. • Modelling the MSWM. • Aggregating the data and handling the uncertainties.
Impact assessment	• Finding resource consumption and environmental impact potential does the treatment entails. • Finding the most important contributions. • Finding the most important sources. • Handling the most significant uncertainties and data gaps.

3.5.2 Phase 2: Life Cycle Inventory (LCI)

At this stage, it is important to inventory data covering waste characteristics and describe environmental impact categories. Data quality plays a key role

in achieving reliable results (ISO, 2006b; EC, 2010). Data selection depends on the pre-defined objective and scope, the degree of data availability, and its relevance to the study topic (Laurent et al., 2014b). After collecting data for each process, emission, and element, analysis programs such as Excel can be used to analyze it, and all data are presented in tables for comparison.

3.5.2.1 Inventory/ Data

The datasets were collected from the Bahrain Open Data Portal, IeGA. To process the detailed calculations in OpenLCA 2.1.1, the Ecoinvent_3.8_cutoff_regio_3011 database was used. The “midpoint of the ReCiPe(I)” was used in the impact assessment method category. The total distances from the center of Askar landfill to the center of the four governorates in Bahrain were calculated using Google Maps. For the main assumptions, the unit transportation process selected from the OpenLCA database was “Transport, Shipping, Truck 3.5-7.5 MT, EURO4” which was considered here to transport the total waste from each governorate to Askar landfill.

3.5.2.2 Sensitivity analysis in LCA

Key sensitive parameters in MSWM are used to determine influential environmental factors such as recycling efficiency, MSW composition, and energy production/recovery rate (Iqbal et al., 2020). In LCA, the environmental impact is calculated, and this process requires validation of the parameters to ensure their accuracy before basing the final assessment on them (Groen et al., 2014). Sensitivity analysis assesses the robustness of the results and the sensitivity to the impact of uncertainty on the data. A sensitive parameter contributes to the variability of the outputs, and changing it

significantly affects the outcome. One way to conduct a sensitivity analysis in LCA is to use the out-of-the-box approach (OAT), where the input parameters in each subset are changed one by one to see how they affect the results. This approach is easy to implement and understand. Sensitivity analysis helps analyze the results and rank the influencing factors according to their impact, thus identifying the factors that most affect the outputs in the model. This method helps decision-makers prioritize policies and rank them according to their degree. Since the data used in all research is a combination of primary and secondary data, it is recommended to use sensitivity and uncertainty analysis. Sensitivity establishes the weight of a constraint in the model, whereas uncertainty originates from outside the system and depends on multiple factors (Heijungs, 1996). Sensitivity analysis can be accomplished using input/model parameter variance or the inclusion/exclusion of a subprocess, extreme scenario conditions. The difference in the final findings is assessed to determine whether it influences the scenario ranking or if it is substantial (i.e., greater than 20%). While the latter is known as scenario analysis, the former is frequently referred to as one-way sensitivity analysis or perturbation analysis (Iqbal et al., 2019; Liikanen et al., 2017).

3.5.2.3 Procedures for Finding the Sensitivity Analysis

In OpenLCA, data sensitivity can be measured by testing the data of one of the operations (Collection, Transport, Treatment), using the IPCC 2013 impact assessment method. Then repeat the procedure for each parameter in each operation and obtain the results as shown in Table 3.4.

Table 3.4: Sensitivity Analysis

Parameters	Collection	Transport_To_Site	Treatment
Mean	20.0	95.1	-4.0
Max_Transport_To_Site	20.0	104.61	-4.0
Max_Collection	22.0	95.1	-4.0
Max_Treatment	20.0	95.1	-4.4
Min_Collection	18.0	95.1	-4.0
Min_Transport_To_Site	20.0	85.59	-4.0
Min_Treatment	20.0	95.1	-3.6

3.5.2.4 Data Cleaning and Analysis

The study uses Microsoft Office Excel 2021 to find duplicate data using the Duplicate Values tool. To evaluate scenarios, the data is arranged to find maximum and minimum values. The Quick Analysis tool in Microsoft Excel 2021 is used to arrange the data. Use the Quick Analysis tool or press Ctrl+Q.

3.5.3 Phase 3: LCIA

LCIA, which comes after inventory analysis and assesses the quantity and implications of possible environmental impacts, is the next essential stage of LCA. The LCIA phase is made up of ISO 14040/44 defined mandatory and optional parts. A key element in impact classification and characterization is identifying the appropriate impact category, such as the impact of GHG emissions on GWP. Data can be further standardized into a common unit, and practitioners can weigh impact categories according to their preferences. There are several LCIA approaches, including CML and ReCiPe, which attempt to predict environmental impacts and differ in their ability to meet all

types of categories and identify potential damages to the environment. There are differences in the results according to each approach (Clavreul et al., 2012). ReCiPe is a highly influential methodology in LCA that combines the strengths of various methods (Rashedi, A., & Khanam, T., 2020).

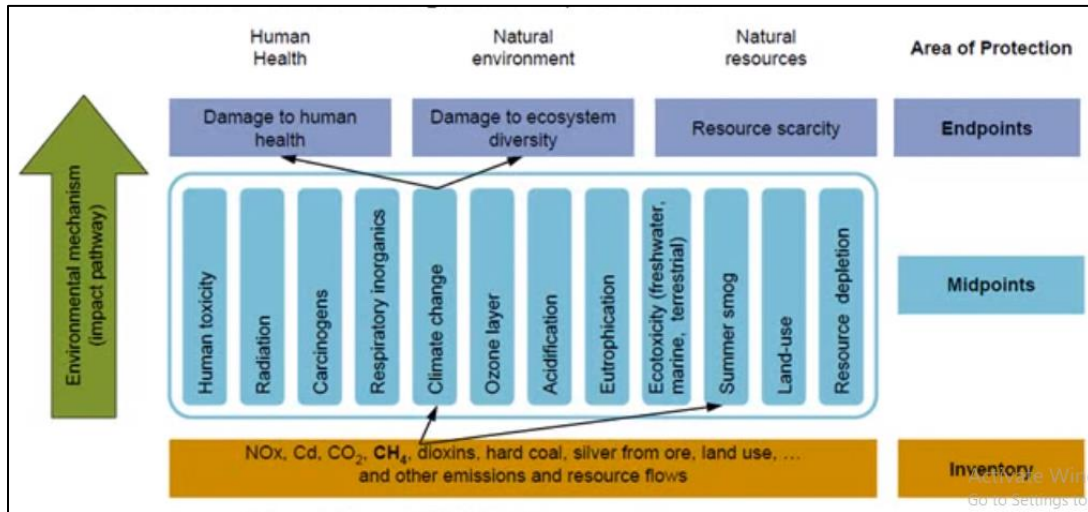


Figure 3.9: Planning LCIA. Source: (ILCA, 2010)

Medium-impact categories are often selected based on stakeholder needs (Huang et al., 2018). Decisions are made after an environmental impact analysis and prioritization (LCIA) (EREF, 2016) as shown in Figure 3.9. In the LCIA phase, impact types (classification), characterization models (computation of class indicator results), and category indicators must be selected (Vargas, Q. R., 2014).

Table 3.5: Choosing the categories. Source: (Rathnayake, M., 2020; EREF, 2016)

Classification	Sorts inventory parameters according to the type of environmental impacts. Emissions are categorized into impact groups based on the possible consequences. What does this emission contribute to?
Characterization	Translate inventory results (emissions, resource use) to potential environmental impacts. Contributions to the various effect categories, quantified. How much does it contribute?
Normalization	Expression of the impact potentials relative to a reference situation. Is that much?
Weighting	Ranking, assignment, or grouping of values according to the different impression potentials. Is it significant?
Method: Recipe Mid-point (Categories)	Includes climate change, acidification, water depletion, eutrophication, human ecotoxicity, urban land use.
Example:	1 CH ₄ =25 CO ₂ equivalents 1 N ₂ O=320 CO ₂ equivalents 1 CO =2CO ₂ equivalents

To assess the environmental impact, the above categories should be chosen as in Table 3.5 to calculate the normalization and find the weighting (Levis et al., 2016). The impact method can be installed through OpenLCA Nexus from <https://www.openlca.org/download/>. Available on OpenLCA Nexus

at: <https://nexus.openlca.org/database/openLCA%20LCIA%20methods> (Figure 3.10). The researcher selects Enter username [malafia], then selects OpenLCA LCIA method, of the latest version (2.4.2).

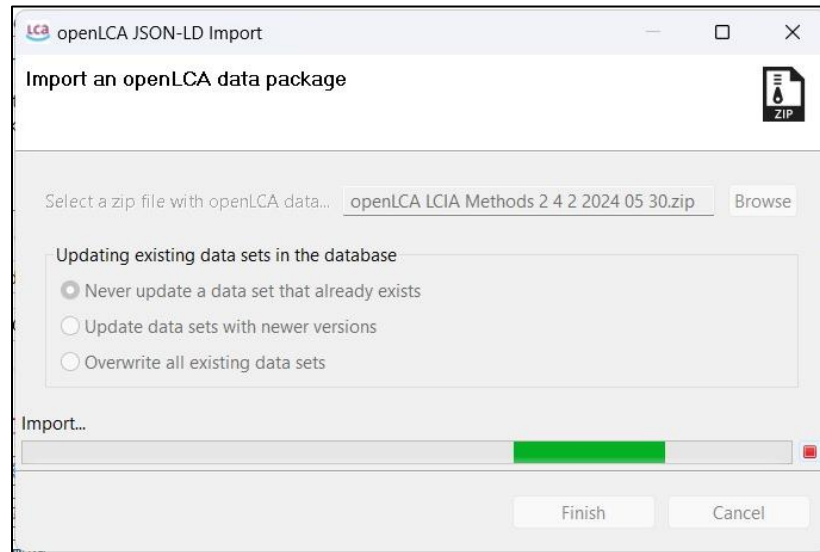


Figure 3.10: Importing OpenLCA data package.

3.5.4 Phase 4: Interpretation

The interpretation phase can be called the optimization phase. In this phase, conclusions are drawn, and data are analyzed. Results are compared to the objectives and scope, and optimization is evaluated. Sensitivity analysis, parameter testing, and data uncertainty are analyzed. In decisions regarding environmental issues, real-world socioeconomic considerations are also considered (EREF, 2016). Identifying critical concerns, assessing completeness, sensitivity, and consistency, and finally drawing conclusions, recommendations, and reporting are important steps in interpreting the results. Involving decision-makers helps in arriving at the appropriate waste management alternative.

3.6 LCA and ISO

ISO has developed a working system for LCA by establishing ISO 14040, for principles and a framework, and ISO 14044, for requirements and guidelines as shown in Figure 3.11 (Olagunju & Olanrewaju, 2020).

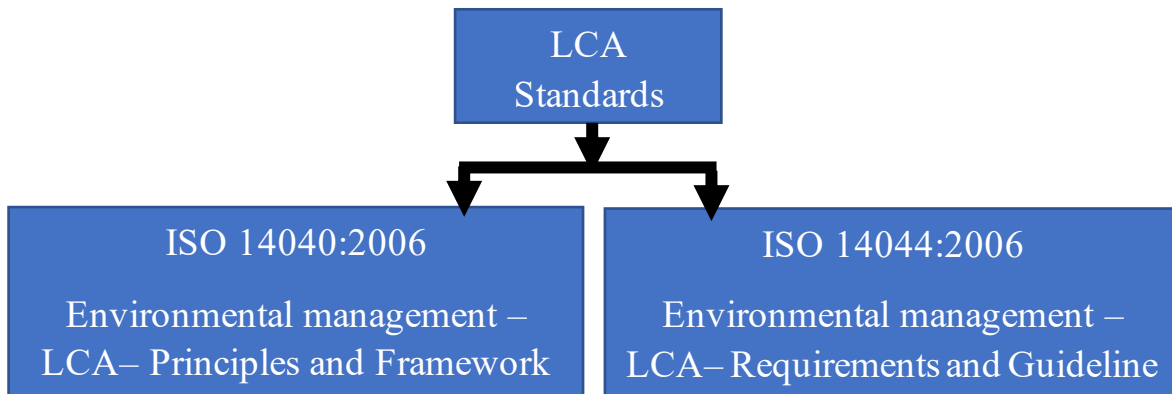


Figure 3.11: Environmental impact assessment protocols, standards, and guidelines. (Created by author).

In the LCA method, opportunities are identified, priorities are set, and indicators are determined to improve the environmental aspects of products and services (ISO LCA 14040, 1997). There are limitations to consider, such as the nature of the options and the limited availability of models used. It is important to understand the limitations of LCA. Local conditions must be understood, not compared to global or regional issues.

3.6.1 International Life Cycle Data System

The JRC and DG INPTA started working on the International Life Cycle Data Reference System (ILCD) in 2005 (Appendix D), to offer standards and guidelines for improved uniformity and quality control when using LCA. The

ILCD guide was created to align with the ISO on LCA (European Commission, 2023).

3.7 Life Cycle Costing

OpenLCA provides an economic study option using the LCC tool to calculate the benefits and costs of each scenario. LCC approach in OpenLCA follows the SETAC Working Group's proposal that costs be modeled by evaluating inputs and outputs (Ciroth, A., 2016). LCC can analyze different types of costs, help support economic decision-making, compare current and future costs, and ensure data reliability.

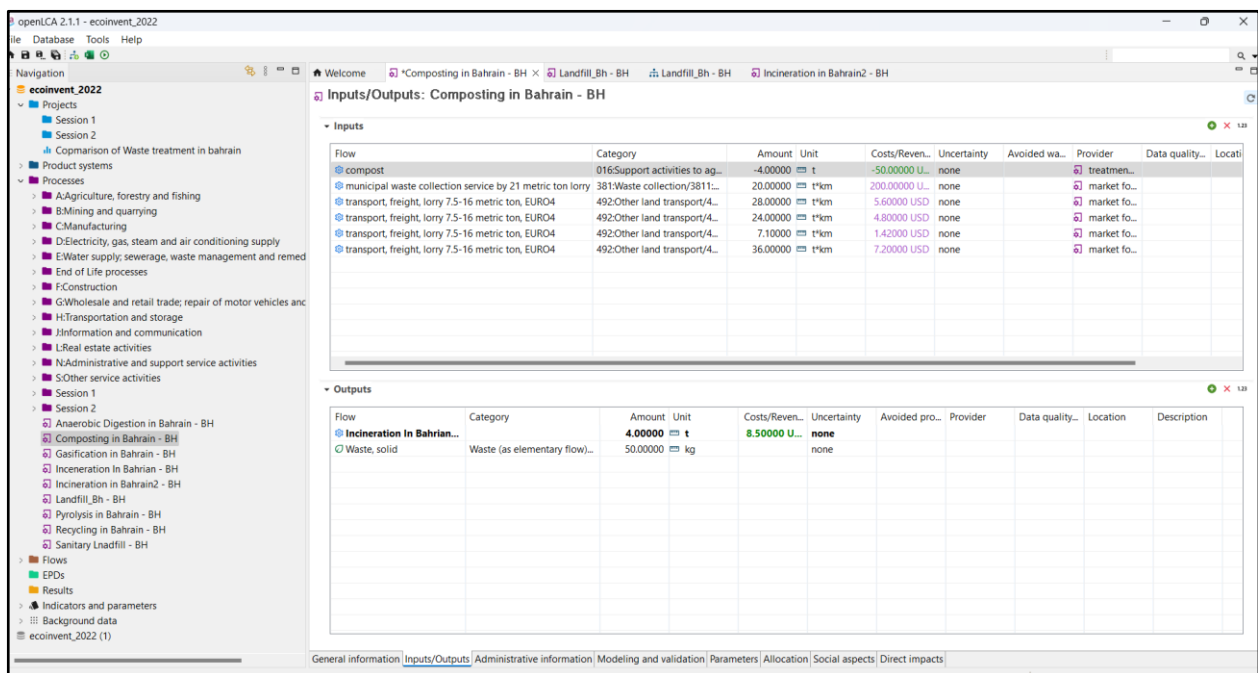


Figure 3.12: LCC tool- Composting cost/revenue in OpenLCA software.

In the Cost/Revenue column, as shown in Figure 3.12, put the amount of the cost of the selected scenario per ton from Table 3.6. Put the cost of collection

of waste (US\$/ton). For transport, put the cost of transport. In Output, put the revenue (US\$/ton).

3.7.1 Using Cost and Revenue in LCC

An estimation method, such as cost modeling based on approximate cost calculations, is used when direct data is unavailable or incomplete (Kambanou, M. L., 2020). When calculating LCC as shown in Figure 3.13, known unit costs defined within the limits (cost/ton) are used. In addition to direct costs, the LCC system also considers indirect costs, such as environmental externalities, such as carbon emissions, and costs after landfill closure or decommissioning. Simplifying the method may affect the accuracy of the results, but it provides a more comprehensive view for decision-makers.

To calculate the cost/revenue, the equation used is:

$$\text{Net Costs} = \text{Total Costs} - \text{Total Revenues}$$

The positive result means a net expense, meaning it costs more than it generates in revenues. The negative result is a net gain (profitability).

The cost of the current waste management method will be calculated. Then, the results will be compared with each method to determine which one is more economically viable. The cost and revenue for each scenario are summed up with the source indicated in Table 3.6.

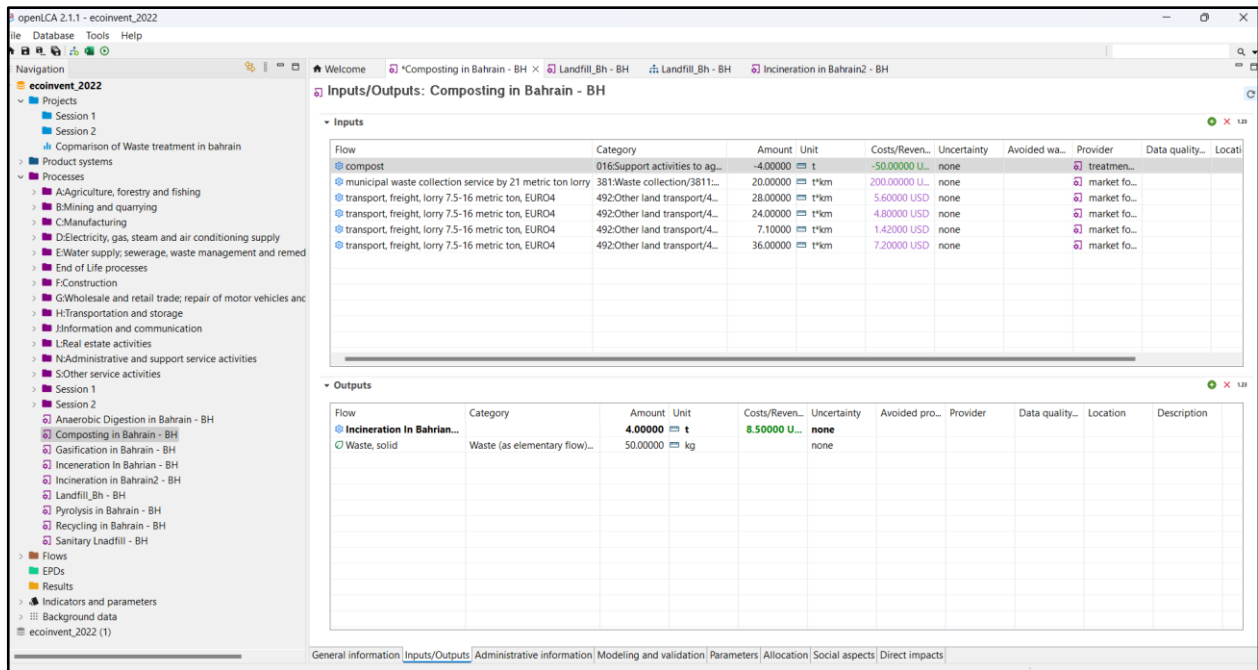


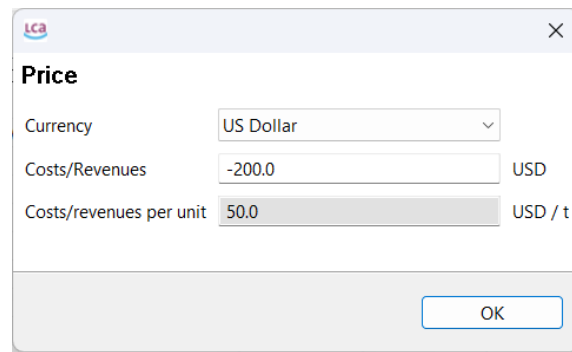
Figure 3.13: OpenLCA software LCC tool- cost/revenue.

Table 3.6: Cost/Revenue for the selected scenarios of MSWM.

Sr.	Scenario	Cost (US\$/ton)	Revenue (US\$/ton)	Reference
1.	Landfill (dumping)	41 US\$/t	6.6 US\$/t	Municipal affairs and the agricultural ministry
2.	Composting	107.5 US\$/t	637 US\$/t	(Chen, Y.-T., 2016) Bahrain market price
3.	Incineration	55.5 US\$/t	100 US\$/t	(Joshi, N., et. al, 2021)
4.	Gasification	115 US\$/t	145 US\$/t	(NREL, 2021)
5.	AD	60 US\$/t	65 US\$/t	(DOE, 2019)
6.	Sanitary Landfill	75US\$/t	97.5 US\$/t	BioCycle (2020)
7.	Recycling	75 US\$/t	155 US\$/t	USEPA (2019, February 15)

3.7.2 Calculating Cost/Revenue for All Scenarios

In OpenLCA, select the database, then select the [Process] component. In the [Input/Output] sheet, select [input] and in the [Cost/Revenue] column, put the amount of the cost of the selected scenario per ton from Table 3.6. By pressing inside the cell of Cost/Revenue, Edit will appear, press it, and a screen will appear as in Figure 3.14.



The screenshot shows a 'Price' dialog box with the following fields:

Field	Value	Unit
Currency	US Dollar	
Costs/Revenues	-200.0	USD
Costs/revenues per unit	50.0	USD / t

An 'OK' button is located at the bottom right of the dialog.

Figure 3.14: LCC for pricing.

Select the currency you want (US\$). Fill in the [Costs/Revenue] value of the selected scenario (do not forget the negative sign). Fill in the [Costs/revenues] per unit (USD /t) and divide it by the number of areas (4 governorates).

Then, in the Input tag, put the cost of collection of waste (50 US\$/ton) multiplied by the number of areas (4 governorates). Assuming the truck capacity is 5 tons. For every 1 tone, the cost is US\$50; for 4 tones, the cost is US\$200.

For transport, fill in the cost of transport for each area: 28 km, 24 km, 7.1 km, and 36 km (the average distances for each governance). Dividing the distance by the capacity of the truck, which is 5 tons, will equal US\$5.6. For the other governorates will be US\$4.8, 1.42, and 7.2. In the [Output] tag, fill in the

revenue (US\$/ton). The cost and revenue for all scenarios are the same as in Table 3.4. In [Product] component: Select the scenario. [Unit]= kg, [Target amount] = 1.0.

In Calculating properties, select (Incineration in Bahrain) [Impact Assessment method]: Ef 3.1 method (Adapted) as in Figure 3.15. Select the two options (regionalize calculation, include cost calculation), then press finish. After that, the result will appear as in Figure 3.15.

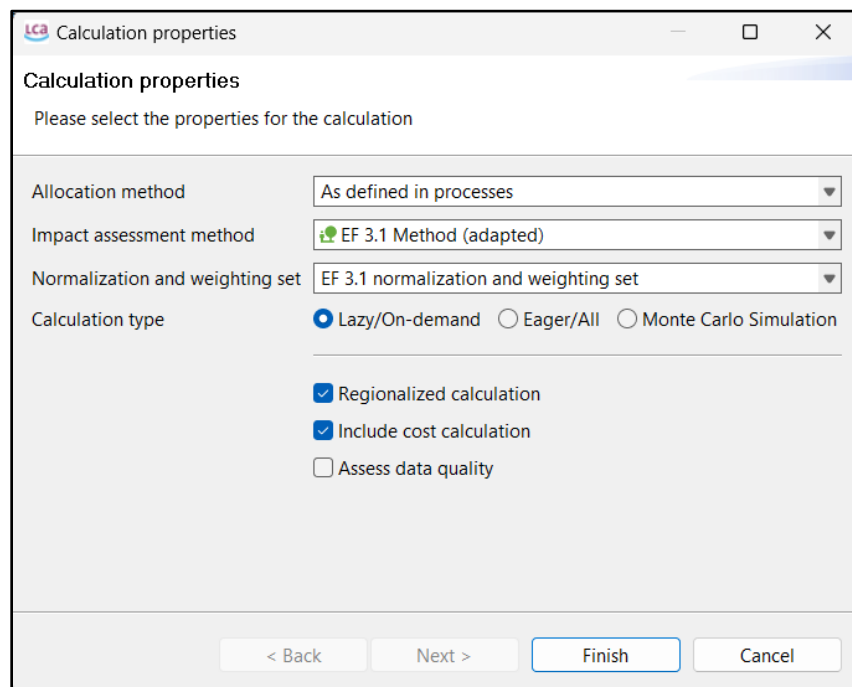


Figure 3.15: Allocating the Impact Assessment method.

The final report of this process can be obtained from the following steps:

In Sheet [contribution tree]. In [cost category] select: Added value. Then you can copy the results or export them into Excel. The same procedures can be done for other scenarios.

3.8 Questionnaire survey

Sustainable development consists of three main pillars: environmental, economic, and social. As illustrated in Figure 3.16, the social dimension of sustainability is a key component of this case study, which can be measured through a quantitative questionnaire. To evaluate the effectiveness of the current MSWM, the research measures the third dimension, the social dimension.

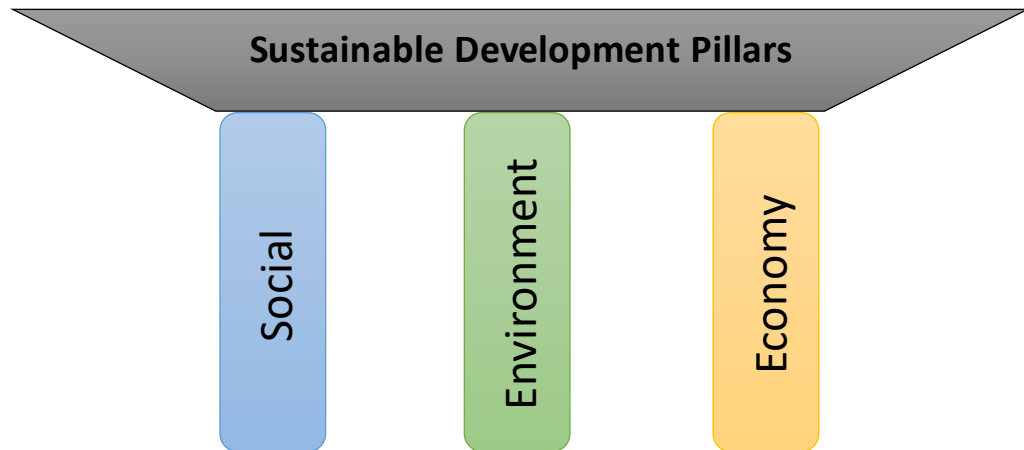


Figure 3.16: Sustainable Development Pillars

The questionnaire explores the community's level of knowledge and awareness of waste segregation and their willingness to practice and cooperate in doing so. The questionnaire was prepared in English and Arabic to cover all citizens and residents of Bahrain. Various sources were used to prepare this questionnaire. These sources are Shaheen et al. (2014), Licy et al. (2013), Abbas, S. (2019), Sreenivas et al. (2022).

The survey questions are aligned with the research objectives, and through them, the data can be used to provide reliable interpretations that benefit the

research and its objectives (Appendix B). They are also suitable for different segments of society and aim to collect primary data to measure the level of community awareness, to build a model applicable to the environment under study. The survey was presented to experts from various disciplines for feedback. It was approved by the University of Bahrain and tested for validity and reliability. It was distributed electronically via email and smartphones using Google Forms. The survey results were analyzed using R and Excel.

The convenience sampling method was used, it is a non-probability method for selecting the units to be included in the sample because it is considered the easiest for the researcher in terms of access, ease of availability at a certain time, geographical proximity, and freedom of desire to participate in the questionnaire (Golzar et al., 2022).

3.8.1 Pilot study

The purpose of conducting a prospective study is to ensure validity and consistency before performing the actual study (In, J., 2017). It is useful for verifying the applicability and feasibility of the research, identifying sampling issues, checking time and cost, gaining experience, and verifying the method, condition, and working conditions of the instruments. The questionnaire link was sent to 25 individuals selected from doctors, PhD scholars, education specialists, and teachers. Nineteen samples were received, and the data were collected from a Google form and saved in Excel for processing. The size of the representative sample is determined through a scientific equation that is proportional to the total size. This study will use the Thompson Equation (Steven K. T, 2012).

$$n = \frac{\left(\frac{Z}{d}\right)^2 x (P)^2}{1 + \frac{1}{N} \left[\left(\frac{Z}{d}\right)^2 x (P)^2 - 1\right]}$$

n: Sample size, N: Population Size, Z: The Confidence level (Confidence Level 95%=1.96, Confidence Level 99%=2.58), d: Error proportion (Confidence Level 95%=0.05, Confidence Level 99%=0.01), P: Probability value=0.05. The population size is 1,212,435 people (for the population over 18 years old).

The population size is the number of Bahraini residents aged 18 years and above. Based on the number of residents present for the study, a simple random sample must be chosen, because the population is very large, if there are variables such as all governorates, so that they are represented in the sample by no less than 20 or 30 people in each governorate, while ensuring diversity between males and females. More than 30 samples must be available to measure validity and reliability. After using the Excel application, the required sample size was 384 people.

3.8.2 Distributing the questionnaire

The main questionnaire was distributed from August 9, 2024, to August 18, 2024, to various segments of society, with 3,841 messages (2,751 via WhatsApp, 1,190 via email), and 1,059 responses were obtained.

3.8.3 The effect of Social Factor on Sustainability MSWM

Through social factors, we can identify the role of individuals and society in sustainable waste management. It also explores the extent to which individuals cooperate with the community and its civil society organizations to advance society. It also allows us to understand the level of awareness

among individuals of the importance of sustainable waste management, environmental conservation, and community cooperation in the success of sustainable waste management. Social factors influence the sustainability of MSWM, including reducing waste production and proper disposal, recycling, responsible consumption, and reducing the use of perishable materials and waste. Segregating recyclable waste is an essential step in its utilization and reuse. One of the roles the community must play in sustaining MSWM is cooperation, awareness-raising, and participation in joint waste management activities (Hapuarachchi, H.D. D. T., 2024). One of these is raising public awareness of the importance of waste management and its environmental and health impacts (Sinthumule & Mkumbuzi, 2019). This also includes encouraging participation in local activities in recycling programs. The community must support innovation and technology to improve waste management and the biological conversion processes of organic waste (Tarigan et al., 2020). The community should participate in community initiatives and environmental campaigns that focus on cleanliness and environmental conservation.

Stakeholder engagement and communication are supposed to improve decision-making. Stakeholder engagement and public information about policy options and the importance of initiatives for their success (Thyberg & Tönjes, 2015).

3.8.4 Missing Value Analysis

The questionnaire was prepared strictly and accurately so that it could not be completed without filling out the entire questionnaire. The options were designed so that no question could be left unanswered, and the answer could not be sent without completing the questionnaire completely. Therefore, all

1059 responses were complete and not missing after entering all the data completely into the R-software.

3.8.5 Validity and reliability

Validity was extracted using a peer review scale approved by the highest authority at the university. Reliability was calculated using Cronbach's alpha formula and the reliability coefficient, which are statistically acceptable reliability coefficients. Kwenda et al. (2022) study household waste management and use R software in their statistical analysis. Sala-Garrido et al. (2024) evaluated the environmental efficiency of the MSW sector in the Czech Republic for the transition to a circular economy and sustainable waste management.

3.9 Interview with experts

The expert interview tool in the field of MSWM aims to explore the three elements: energy, technology, and economic efficiency, which constitute some of the elements of the proposed SELECT model. It also explores the tools, administrative alternatives, and opportunities available to decision-makers to develop the best and most environmentally friendly MSWM policy. The best waste collection methods, opportunities for environmental improvement, and the effectiveness of economically efficient waste management are explored. The expert interviews also help assess Bahrain's readiness to treat separated waste and propose ways to implement it. The interviews also explore the importance of conducting an economic feasibility study before making any decision regarding waste management with the highest economic efficiency.

3.9.1 Designing an Interview

Interviews are used as qualitative empirical research methods to explore knowledge and gather information and facts. Individuals can be considered experts who possess knowledge, and researchers can explore this knowledge with individuals. The semi-structured interview questions were designed to be conducted with experts and professionals in the field of waste management to explore the three elements (energy, technology, and cost-effectiveness) of the proposed SELECT model. A semi-structured interview allows interviewers to focus while giving the researcher the independence to explore relevant ideas that may arise during the interview, which may enhance understanding of what is being assessed (Adeoye-Olatunde & Olenik, 2021). The interview was oral and consisted of specific questions for each of the required objectives. The interview was conducted in the language of the respondent's choice (Arabic or English), and the questions are attached in Appendix A. Some believe that a typical sample size for case studies ranges from 5 to 30 participants (Creswell, J.W., 2018).

3.9.2 Advantages and Disadvantages of Interviews

The interview technique contributes to obtaining specific details about the topic under investigation. It is a flexible technique that enables the researcher to engage in dialogue with the interviewees to gather information and obtain more details. Qualitative interviews can enrich studies with social phenomena, human experiences, and perspectives (Lim, W.M., 2024). Qualitative methods explore nuances such as characteristics and contradictions in phenomena, providing rich insights linked to a deep understanding for formulating effective, sensitive, and relevant interventions or solutions.

On the other hand, its drawbacks include the time and effort it takes, and the vulnerability of the researcher's emotions, which may lead the participant to provide the answer the interviewer prefers. This technique requires skills and knowledge of the topics being discussed, as interviewers may need more details. Participants may feel uncomfortable being recorded, which could influence their answers.

3.9.3 Ethical Considerations

Participants were informed before the interview of the purpose of the interview and were given their consent not to disclose the questions so as not to influence their opinions. They were assured of the confidentiality of the interview and the privacy of their data, ensuring their answers were transparent and without restrictions. This allowed them to feel comfortable during the interviews and to freely share their opinions and personal experiences.

3.9.4 The Interview Protocol

Individuals from various disciplines, whether in waste management or sustainable development, and those with contributions in this field were selected. Participants ranged in practical experience from various governmental, non-governmental, and private sectors. Thirteen interviews were conducted between August and September 2024, with each lasting between 30 and 80 minutes. The interview questions and answers are included in Appendix A.

3.9.5 Interview Data Analysis Method

In qualitative research, data analysis involves gathering similar ideas. It all depends on understanding what interviewees say, organizing responses, and analyzing and interpreting the responses. Details of the interview results are collected in Chapter Four, along with their analyses and illustrative charts. Technology has provided the ability to analyze, process, and interpret qualitative data deeply and accurately, including the emergence of artificial intelligence, which enriches the insights obtained and enhances research efficiency (Lim, W. M., 2024).

Table 3.7: Interviewer data and details

Serial	Details	Date	Duration	Language
1.	President, Municipal Council, Environmental Law PHD,	21 st August 2024.	11:15 -11:45 am	Arabic
2.	Specialist in Environment. PHD In Environment sustainable development.	24 th August 2024.	11:15 am- 11:50 am	English
3.	Consultant in Environment, Environment Arabia Consultance.	11 September 2024.	3:00 -4:10 pm	English
4.	Specialist in Hazardous Waste, Supreme Council for Environment.	15 th September 2024.	9:22-10:20 am	Arabic
5.	Head, Urbaser Cleaning Company	15 September 2024.	9:25- 10:12 am	Arabic
6.	Head, Waste Management, Directorate.	15 September 2024.	10:57-11:13 am	Arabic
7.	Consultant in Waste Management,	15 September 2024.	11:14- 11:53 am	English

8.	Environment Arabia, Managing Director.	9 October 2024	12:24 – 01:29 pm	Arabic
9.	Member of the Shura Council, PhD in Environmental Sciences.	22 October 2024	12:49- 1:34 pm	Arabic
10.	Operational manager, GCCC Cleaning Company	20 October 2024	3:00- 4:30 pm	Arabic
11.	Executive Manager, Crown Industries.	21 October 2024	11:19- 12:47 pm	Arabic
12.	Head of Coordination and Information Department, Northern Area Municipality.	20 October 2024	8:54 – 9:52 pm	Arabic
13.	GM of Urbaser Cleaning company.	22 October 2024	9:59- 10:53 am	English

Table 3.7 summarizes 13 expert interviews conducted from August to October 2024 with professionals in environmental law, waste management, and municipal services. Interviews, held in Arabic and English, lasted 16 to 90 minutes and included stakeholders from government, private sector, and consultancy firms.

3.9.6 Interview Method and Procedures

A qualitative content analysis method was used to analyze the interview (Thukral and Singh, 2023). The first step is to extract relevant data from the interviews provided. The second step is to categorize responses based on recurring themes and individual perspectives. The third step is to identify patterns and areas of agreement and disagreement. The fourth step is to quantitatively analyze to measure consensus. The fifth step is to compare responses. The final step is to identify actionable conclusions.

The scientific tools used are text organization, thematic analysis, quantitative analysis, tabular comparison, and synthesis writing. By following these steps, the analysis provides qualitative and quantitative insights into expert perspectives, facilitating the identification of actionable recommendations.

3.10 Assessing the Achievements of SDGs Related to MSWM in Bahrain

This section reviews the assessment of Bahrain's achievements of the SDGs, whether the goals are directly related to MSWM or the goals indirectly related. These achievements were taken from the first voluntary national report VNR1 in 2018, the second national review VNR2 in 2023, and the government plan.



Figure 3.17: Relationship of Direct and Indirect SDGs Vs. MSWM.

The research then reviews a table to assess these achievements. Before all that, the researcher conducted a review of all SDGs (17) and their targets (229) and

their indicators (247) to find out everything related to waste management directly or indirectly. Figure 3.17 shows the SDGs direct (the inner circle) and indirect (the outer circle) related to MSWM. These achievements are evaluated and described in relative terms against the criteria adopted in Chapter 2. Rashed, A.H. (2022) study revealed that environmental legislation in the Kingdom of Bahrain keeps pace with the SDGs, and he sees this through recognizing the challenges highlighted by the 2030 Agenda.

3.10.1 Process of Assessment of SDGs

The 1-5 scale is calculated for its simplicity, ease of interpretation, and communication, as it consists of only five points, and is easy to compare. It also provides a straightforward way to summarize progress and compare different SDGs or categories. Descriptive scores were used to link each score (1-5) to the descriptive scores as follows:

1. Little progress: No significant actions or results have been achieved.
2. Limited progress: Some actions have been taken, but with limited results.
3. Moderate progress: Significant improvements but significant gaps remain.
4. Substantial progress: Significant results with small gaps.
5. Exceptional progress: Goals have been achieved or are close to being achieved.

3.10.2 Bahrain Voluntary National Review

This section summarizes the most important achievements for direct SDGs with MSWM of the first voluntary national report of Bahrain 2018 (VNR1) (IeGa, 2021) and the second voluntary national report of Bahrain 2023 (VNR2).

Table 3.8 highlights Bahrain’s progress towards the SDGs directly related to MSWM initiatives, comparing VNR1 and VNR2. The 2023 report (VNR2) demonstrates a marked shift from foundational policies to more specific and measurable actions. Key developments include the implementation of the National Waste Management Strategy (2018), the ban on certain plastic products, and the regulation of hazardous and electronic waste. VNR2 also presents practical accomplishments such as high recycling rates, the processing of hazardous waste into value-added products, and innovative food redistribution efforts. These achievements align with SDG 11 (sustainable cities), SDG 12 (responsible consumption and production), and SDG 13 (climate action), reflecting an evolution from general policy frameworks (as seen in VNR1) to targeted, on-the-ground interventions that support sustainability and pollution reduction goals.

Table 3.8: SDGs directly related to MSWM.

SDGs	VNR1	VNR2
11.3	- Focus on clean renewable energy. - Smart cities, sustainable communities with low carbon. - A legal framework to reduce pollution helps improve waste management. - Bahrain issued Resolution No. (10) of 1999 regarding	- Bahrain International Airport was awarded the Green Airports Award in the Silver category for its focus on waste management and reducing carbon emissions. Recognized as a distinguished airport with a Leadership in Energy and Environmental Design (LEED), recycling rate of 22.14% and

11.6	environmental standards to address the effects of air quality, increasing waste, and limiting gaseous and liquid emissions. - 100% waste collection and transportation. - Disposing of hazardous waste in the “Hafira” landfill. - Ratifying the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes. - A statistical system for industrial waste is created and submitted to the Basel Convention Secretariat. - Preparing a plan to manage hazardous industrial and medical waste, and a plan to recycle electronic devices. - Adopting a policy of global partnerships in the field of financing, capacity building,	diverting 77.91% of construction waste away from landfill. - Adopting waste reduction measures and recycling initiatives in industrial sectors. - Approximately 95,000 tons of waste were recycled in 2021, approximately 130,000 tons of waste were imported for use in production activities, and 325,000 tons were exported for recycling and recovery purposes. - The National Waste Management Strategy (2018) is based on sustainable development. - In 2021, Bahrain issued regulations related to the management of electronic and electrical waste in a sound, safe, and sustainable manner to protect public health and the environment. - Decisions were issued to ban importing non-biodegradable plastic bags, the manufacture, of plastic water bottles and cups with a smaller than 200 ml, and the
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11.c	providing modern technology and waste recycling. - Adopting the concept of sustainable buildings and construction, reducing the percentage of construction waste by 50% to 75%.	import, manufacture, and distribution of single-use plastic bags with a thickness of less than 35 microns. - In 2020 cooperation with the World Health Organization, addressing the handling of hazardous medical waste from production to disposal, and there is tightening and monitoring of this by Bahrain, conducting annual inspections. - Alba processes hazardous waste estimated at 36,000 tons annually and converts it into a value-added product. - The Food Bank of Bahrain collects and packages surplus food from various locations and redistributes it to those in need across the Kingdom. The society has preserved more than 1,920,000 meals and distributed them to more than 1,800 families, 10,000 individuals and 5,000 expatriates.
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		- The Supreme Council for the Environment has installed a new methane gas collection system at the Askar landfill, covering about 20% of its total area.
12.3	- Focus on urban development options. - Central markets have been adapted to reduce food spoilage and waste.	- Organizing legislation and regulations related to the management of plastic, hazardous and electronic waste.
13.1 13.2 13.3	- Taking several steps to address the climate. - The legal framework for reducing pollution contributes to mitigating global change.	- Law (7) was issued regarding the environment in the field of dealing with the issue of climate change. - Bahrain joined the global methane emissions reduction treaty in 2021 and pledged to reduce the rate by 30% by 2030.

Table 3.9 outlines Bahrain’s progress in achieving the SDGs indirectly related to MSWM, demonstrating how integrated waste strategies contribute to broader national development outcomes. While VNR1 laid the foundation through legal and economic reforms—such as job creation, unemployment reduction, and establishing the 2005 National Strategic Master Plan—VNR2 demonstrates a deeper integration of environmental sustainability within economic and technological frameworks. Notable contributions include the

promotion of circular economy principles, advances in technological infrastructure, and increased public-private sector collaboration. These measures indirectly support SDG 3 (good health), SDG 8 (decent work and economic growth), SDG 9 (industry, innovation, and infrastructure), SDG 14 (life below water), SDG 15 (life on land), and SDG 17 (partnerships for the goals). The joint efforts reflect how MSWM plays a pivotal role in promoting human health, protecting the marine environment, innovation, and sustainable economic development.

Table 3.9: SDGs indirectly related to MSWM.

SDGs	VNR1	VNR2
3.9	- The legal framework enacted by Bahrain contributes to reducing pollution to human health.	-
8.2	- Reduced unemployment by 4%.	- The Labor Fund (Tamkeen) sponsors the development of human capital, and if investment in waste sorting and recycling is activated, job opportunities will be created for citizens.
8.3	- Made Bahrain an attractive environment for investment	
8.5	- Provided job opportunities for citizens. - Resolution 2005 National Strategic Master Plan to achieve balance and land uses. - Focus on diversifying non-oil sectors.	

8.6	- Strengthening partnership with the private sector and civil society institutions.	
9.5 9.b	- Care for innovation and knowledge. - Improving technological capabilities. - Tamkeen works on the quality of services and achieving innovation. - Collecting and publishing data through the Bahrain platform. - Rationalizing consumption and directing the public.	- There are several steps taken by Bahrain to accelerate the pace of digitization and technological progress (SDG 9). - Focusing on technological infrastructure and digitizing manufacturing and adopting the concept of a circular carbon economy for environmental and social governance, and here is an opportunity for waste managers to capitalize on this will.
14.1 14.c	- Working to improve waste management helps to save our oceans and seas from pollution. - Beach cleaning campaigns. - The Supreme Council for the Environment has established the	- Enacted legislation to combat marine pollution to protect seawater from increasing acidity. - Awareness campaigns and beach clean-up initiatives sponsored by the government, or

	legal framework to reduce marine pollution.	the private sector help preserve life underwater.
15.1	- Protect ecosystems and halt biodiversity loss.	- Issue executive regulations for biosafety, to approve the
15.5	- Protecting ecosystems requires improved waste management.	National Biosafety Action Plan, which was completed in 2022.
15.8	- Regulating marine fishing in its types, categories, and time.	
15.9		
17.7	- Organizing cleaning campaigns in cooperation with the private sector and various civil society groups. The Ashura campaign has been ongoing for 15 years.	- Cooperating with the private sectors, universities, and schools in cleaning beaches.

After reviewing the achievements related to MSWM under the SDGs, a score is awarded for each achievement, whether legislative, regulatory, or practical. A final score is then assigned based on the specific targets and criteria derived from the literature review. The results of the assessment of the extent to which the goals related to MSWM were achieved are presented in Chapter Four.

3.10.3 Assessment Method for SDGs Achievements in MSWM of Bahrain

This section uses the following systematic method to evaluate Bahrain's achievements in the SDGs concerning MSWM.

First, all 17 SDGs, their targets, and indicators were reviewed, and targets directly and indirectly related to MSW were classified (Figure 3.11). Second, data were collected from the VNR1 and VNR2 (IeGa, 2021). Third, achievements were classified according to legislative achievements, hazardous waste management frameworks, and international agreements, as well as practical achievements, initiatives, infrastructure, and policy achievements. Fourth, the evaluation process was based on assigning relative scores to each achievement based on impact, significance, sustainability, and comparability criteria. Impact refers to effectiveness in achieving the SDGs. Significance refers to alignment with the SDGs. Sustainability refers to long-term benefits and integration into broader policies. Fifth, a comparative assessment of achievements was conducted for each SDG. Sixth, challenges were identified, barriers assessed, and opportunities explored. To assess the SDGs related to MSW, scores were assigned based on indicators of progress, achievements, and challenges. This methodology evaluates progress on a scale from 1 (minimal progress) to 5 (exceptional progress).

3.11 Summary of Chapter 3

The research methodology to applied to achieve all four objectives. A LCA methodology using OpenLCA was applied to evaluate the environmental performance of MSWM scenarios in Bahrain, achieving the first objective. A framework was developed to assess Bahrain's alignment with SDGs 11, 12, and 13, achieving the second objective. For the third objective, LCC was incorporated to evaluate the cost-effectiveness of alternative scenarios, while qualitative data from stakeholder interviews provided insights into managerial feasibility. Finally, scenario modeling and SELECT criteria were used to identify appropriate technological pathways, achieving the fourth objective.

Chapter 4. Results, Discussion, and Recommendations

4. Introduction

This chapter includes results, discussion, and analyses that answer the research questions and achieve its objectives. It presents the results in the form of tables and illustrative figures with an explanation. The discussion links to previous studies, whether they prove or refute the results. The chapter presents the most important recommendations and appropriate procedural proposals. It also presents recommendations that contribute to addressing the problem in the form of brief procedural points. Finally, recommendations for future research are presented.

4.1 Modelling of MSWM

This section presents the outcome of simulating the phases of the MSW system and its effects on the environment. Here, the best waste management scenario is extracted by analyzing the waste management system and comparing environmental impact data for each scenario. The Ecoinvent 2022 open landfill database was used. The predominant method in Bahrain is landfilling, which releases gases directly into the atmosphere. The OpenLCA program assesses the environmental impacts, quantifying emissions to air, water, and soil, and comprehensively evaluating inputs and outputs for all scenarios. An emission standard of 7.5–16 metric tons was assumed for trucks transporting excavated material, in line with Euro 4. The assumption here refers to emissions per truck. For the non-sanitary landfill treatment option, the "Extremely Dry Leakage Class (-250 mm) MSW Consequential, S-GLO" was selected.

4.2 LCA results

The tables and graphs in this section represent the results of the LCA of net emissions from a waste management system from the Ecoinvent database. The results for each of the listed environmental impact categories reflect the total of positive and negative values from the waste management system. It should be noted that when emissions are less than the emissions saved in the background system, the net result is negative. Therefore, results with a negative sign indicate avoided impacts. This section also explains the normalization, validity, and reliability of the data. It then discusses the remaining three stages of LCA: life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation.

4.2.1 Normalization

Normalization is the process of expressing the effect potentials relative to a reference scenario to place a study on a comprehensible standard scale (Pizzol et al., 2017). Weighting is the process of ranking or scoring each effect category's contribution to the total effects. Table 4.1 shows the normalization factor, and the unit impact category used from OpenLCA software. Normalization factors are usually positive; however, if they are negative, as in the case of terrestrial acidification ($\text{kg SO}_2 \text{ eq} = -3.99586\text{E-}06$), it indicates that the reference acidification impact data may have net negative emissions, possibly due to acidification mitigation or emission reduction activities. This may indicate a problem with how the reference system calculates acidification, or perhaps from data inconsistencies. A negative value for urban land occupation ($\text{m}^2 \text{ a} = -2.36411\text{E-}06$) may mean that land occupation in the reference system has some recorded net negative impacts. The unit $\text{m}^2 \cdot \text{a}$

(square meters times years) means using 1 square meter of land for one year, and it's used in LCA, especially for land use impacts.

Table 4.1: Normalization of impact categories (OpenLCA)

Environment Impact	Reference unit	Normalization Factor
Climate change	kg CO ₂ eq	0.000136102
Freshwater eutrophication	kg P eq	0.000179096
Human toxicity	kg 1,4-DB eq	0.000165447
Terrestrial acidification	kg SO ₂ eq	-3.99586E-06
Urban land occupation	m ² a	-2.36411E-06
Water depletion	m ³	0

This may be due to land restoration projects or urban expansion. This is unusual in LCA, as land occupation is generally a positive value (indicating environmental burden). A normalization factor for water depletion (m³ = 0) set to zero may mean that no reference water depletion impact is assigned. This may be due to a lack of available reference data.

4.2.2 Impact Assessment Method Validation and Reliability

The validity and reliability of the impact assessment method in LCA are checked to confirm the strength and consistency of the results. Validity ensures that the method accurately measures what it purports to measure. One way to validate is to base it on scientifically accepted models, such as the IPCC, for calculating the GWP. To validate a life cycle impact assessment method, it should ensure that all categories of impacts relevant to the system under study are included. Additionally, the impact assessment approach must

align with the LCA's goal and parameters. Peer-reviewed, validated techniques like CML or Recipe can be used to check validity. Reliability means ensuring that the method produces consistent results under the same conditions. Reliability can be checked by repeating the analysis with different datasets or models; if the results are consistent, they are reliable.

Table 4.2: Reliability of data by comparing two methods (ReCiPe 2016 and IPCC 2021) with climate change.

LCIA Method	ReCiPe Midpoint (I)	IPCC 2021
Anaerobic Digestion	0.14303648	0.156111721
Composting	0.011590463	0.011657297
Gasification	0.577590463	0.577657297
Incineration	0.008355936	0.008346203
Landfill	1.296205289	1.52149023
Recycling	0.00903597	0.008687296
Sanitary Landfill	0.005670954	0.005668396

They can also be checked through sensitivity analysis, uncertainty analysis, and the use of established databases such as Ecoinvent and GaBi. The study can also be compared with comparative studies to check validity and reliability. Validity involves whether the research design and method produced an accurate measurement of what was intended (Flemmer, C., 2020). To evaluate the validity of the effect assessment method used in the study, it is possible to compare two different impact assessment methods. This can be done by comparing two different methods on the same impact category and containing the same units to see the degree of difference, as in the results of

Table 4.2. Climate change can be measured using the ReCipe 2016 (I) midpoint [OpenLCA LCIA Methods 2.4.2] and another method, such as IPCC 2021 [OpenLCA LCIA Methods 2.4.2]. The impact is assessed according to the differences between the assessment methods.

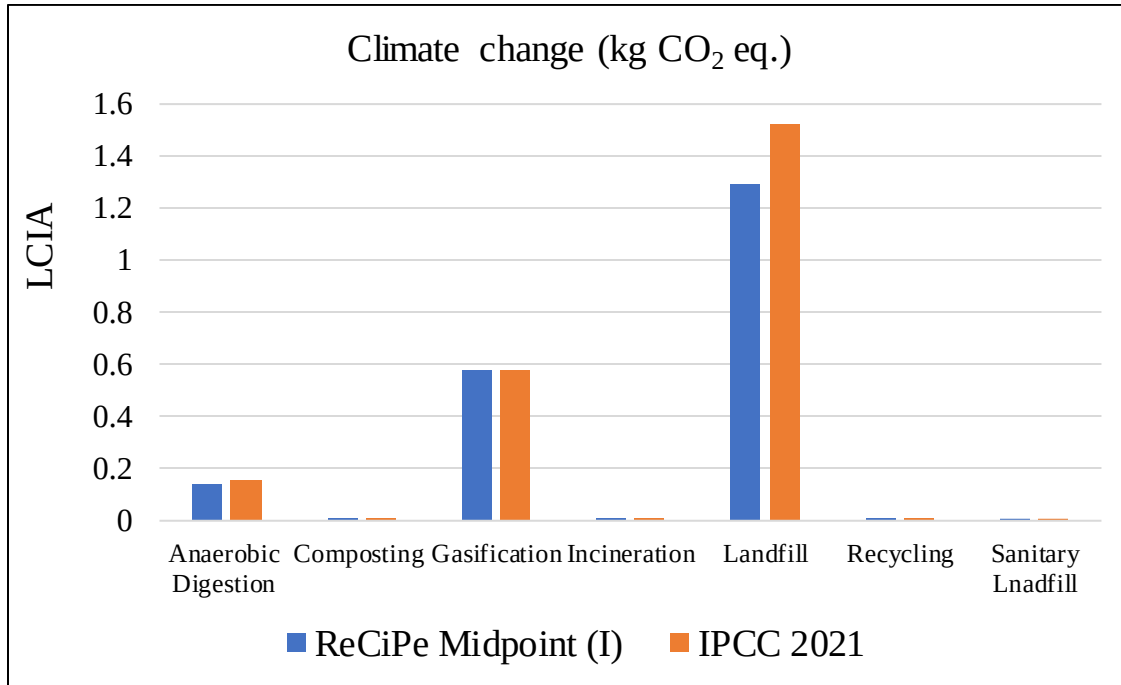


Figure 4.1: Reliability Analysis with Recipe (midpoint(I) and IPCC 2021 impact assessment methods.

It is clear from Figure 4.1 that there are no big differences between the effects evaluation in both methods (ReCipe 2016 and IPCC 2021), as the difference is less than 0.5% for each scenario.

4.2.3 Sensitivity Analysis

The study's main parameters can be evaluated by performing a sensitivity analysis for one parameter at a time (Erhun, M., 2022). In this method, the parameters are changed one by one to find the element that has the greatest effect on releases. Three parameters, namely collection, transportation, and

treatment, are tested by setting the values of each and finding the minimum, maximum, and mean of each as shown in Table 4.3.

Table 4.3: Min, Max, and mean for transportation, collection, and treatment.

Parameter	Climate change
Transport	kg CO ₂ eq
Min	0.501848
Mean	0.50236
Max	0.50287
Collection	kg CO ₂ eq
Min	0.501713
Mean	0.50236
Max	0.503005
Treatment	kg CO ₂ eq
Min	0.45328
Mean	0.50236
Max	0.551438

In OpenLCA software, one of the scenarios chosen, let it be landfill, and select the [Parameter] sheet, which allows users to define numerical values for certain aspects of the waste management system. In this case, the input section has three parameter values and typically represents environmental impact units per ton of waste. 20.0 kg CO₂-eq/ton for collection (due to fuel, labor, vehicles, etc.). 95.1 kg CO₂-eq/ton for transportation (distance-based emissions, likely longer transport route or heavier vehicle). -4.0 kg CO₂-eq/ton for treatment. These values are chosen based on real data, and designed to

reflect specific local conditions in Bahrain, used to run sensitivity analyses. Adjusted to simulate policy impacts, technology changes, or optimization of the waste stream. In the [Dependent] parameters section, set the parameters (transport1, transport2, transport3, transport4) representing the four governorates and set the values 7, 35, 23, and 27 km. Then click on [create product system] and when it gives the result in the product, create (Mean) and click on [add parameter] set. Then, make the parameters as in Table 4.3. In the parameter values, increase 10% each time, choose the IPCC 2013 method, then click on calculation, and the result is as in Figure 4.2.

This process describes a sensitivity analysis in OpenLCA, where each parameter (collection, transportation, treatment) is increased and decreased by 10%, and the resulting changes in the model output (total environmental impact) are compared. This means that the original values (20.0, 95.1, and -4.0) were affected by +10% (22.0, 104.61, -3.6) or -10% (18.0, 85.59, -4.4). This is considered Important because it checks how sensitive your results are to changes in input values. If min and max results differ significantly from the mean, then that parameter is sensitive; small changes have a big impact. If changes in the parameter cause little change in the result, the parameter is less influential. This process identifies key drivers in the model. Using $\pm 10\%$ is common in deterministic sensitivity analysis, especially when the uncertainty range is not known exactly. It's simple and consistent, provides a first-level approximation of influence, and allows comparison across parameters under the same margin of change.

From Figure 4.2, there is more sensitivity analysis in the treatment option. While there is less sensitivity analysis in both the collection and transport to

the site. This indicates that focusing on the treatment parameter is a significant consideration for this study and analysis.

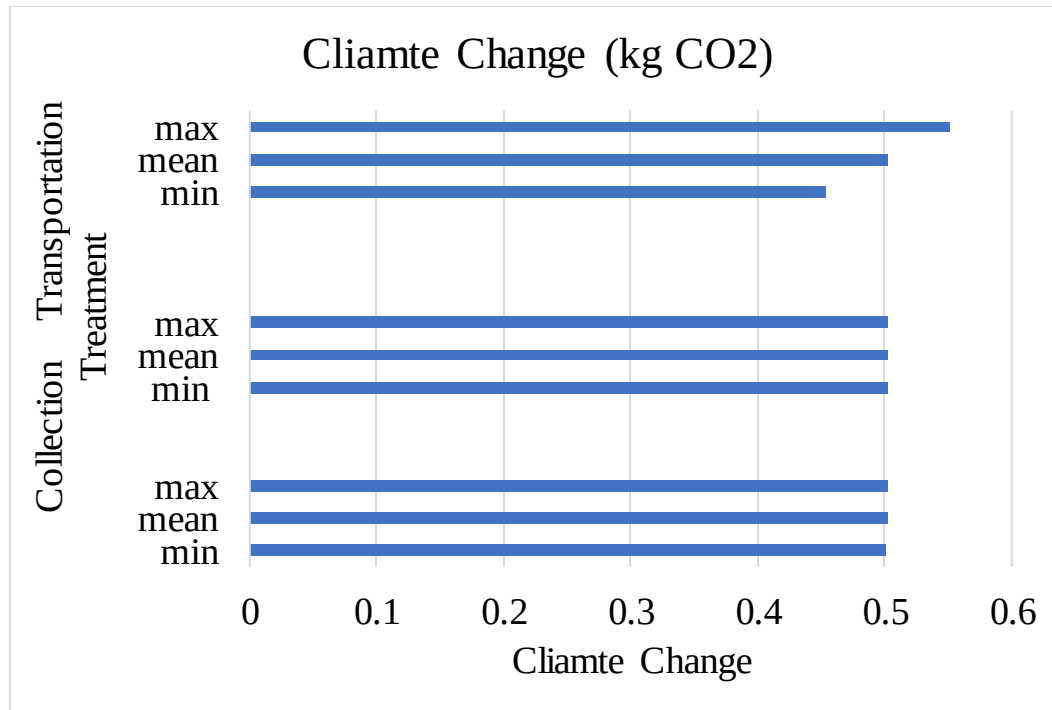


Figure 4.2: Sensitivity Analysis of Climate change in three parameters using the IPCC 2013 method in OpenLCA.

4.3 The Environmental Impacts (OpenLCA results)

After entering all the data and related details, OpenLCA gives a summary table of all the environmental impacts it measures. Table 4.4 shows the descriptive data of each scenario.

4.3.1 Phase (2) LCI

In this phase, data is extracted by using OpenLCA into the inventory results to determine its statistics and analyze it to extract benefits and implications.

Standard deviation is the amount of divergence of all deviations, that is, the average rate of all deviations, and this helps us understand the amount of dispersion. The data Analysis tool (MS Excel) provides Data Descriptives (Table 4.4), which helps the analyst to understand the data. Measure data consistency in each scenario, for example, in the anaerobic digestion scenario. Relying on data analysis in MSW is useful in making sustainable decisions, which can significantly reduce environmental pollution (Oyebode & Abdulazeez, 2023). To ensure consistency and harmony of data, as in waste management principles, input must equal output (Flemmer, C., 2020).

Table 4.4: Data Description

(AD: Anaerobic Digestion- C: Composting- G: Gasification- I: Incineration- L: Landfill- L: Recycling- SL: Sanitary Landfill)

indicator	AD	C	G	I	L	R	SL
Mean	0.0000218	0.0000032	0.0000185	-0.0000086	0.0003075	0.0000226	-0.0000008
Standard Error	0.0000075	0.0000012	0.0000106	0.0000079	0.0002085	0.0000176	0.0000007
Median	2.077E-13	3.107E-14	3.114E-14	1.002E-14	-1.520E-13	-5.840E-15	-5.551E-16
Mode	0.000	0.000	0.000	0.000	-9.51E-17	0.000	0.000
Standard Deviation	0.00208	0.00034	0.00293	0.00217	0.05739	0.00484	0.00019
Sample Variance	0.000004	0.00000012	0.000009	0.000005	0.003293	0.000023	0.00000004
Skewness	136.549	170.216	190.832	-189.312	190.579	109.350	-128.594
Range	0.330	0.063	0.566	0.471	11.375	1.224	0.046
Minimum	-7.18E-12	-4.35E-12	-4.35E-12	-0.419	-0.289	-0.414	-0.033
Maximum	0.330	0.063	0.566	0.052	11.086	0.810	0.013
Sum	1.65	0.24	1.40	-0.65	23.29	1.71	-0.06
Count	75760	75760	75760	75760	75760	75760	75760

From the descriptive statistics in Table 4.4, it is found that the mean reflects the general trend of the values; the largest is landfill (0.0003075). The standard error gives an idea of how accurate the estimate is compared to the mean; small values indicate higher accuracy. For example, sanitary landfill (0.0000007) has a relatively small standard error, meaning it is more reliable. The median represents the middle value of the data and is more resistant to outliers than the mean. Small values in all scenarios indicate that most of the data are close to zero or have little impact. Standard deviation measures how dispersed the values are around the mean, the larger the standard deviation, the greater the variation in the data. The data indicate that the largest standard deviation is for the landfill scenario (0.05739), indicating a high degree of variation in the data for this scenario. Sample variance measures how spread out the data are; the landfill (0.003293) has the largest variance, indicating that its data is more dispersed. Skewness measures how far the data distribution deviates from a normal distribution. Positive values mean that the data is heterogeneously distributed toward large values. All scenarios have positive skewness, meaning that some high values influence the data. The range indicates the range of variation in the data; sanitary landfill (11.375) has the largest range, meaning there is a significant difference between the small and large values. Minimum and Maximum identify the smallest and largest values in each scenario. For example, the largest value was for landfill (11.086), while the smallest value was for incineration (-0.419). The sum is the sum of all values for each scenario. Larger values here mean a higher overall impact. Again, the landfill (23.29) has the highest value, indicating that it may be the most influential in the data.

Overall, through a general analysis of the entire dataset, the landfill scenario appears to have the largest mean and standard deviation values, indicating that it is the most variable and influential. The composting and sanitary landfill scenarios have the lowest mean and standard deviation, indicating that they are more stable and less variable. All scenarios have positive skewness, meaning that there are extreme values that influence the data.

To evaluate the validity of the research method and the reliability of the data in the LCA method as a research methodology for measuring the environmental impact of MSWM, environmental input-output analysis is used. These categories come from Ecoinvent v3.9 Documentation, ILCD Handbook, ISO 14044:2006, and OpenLCA Documentation.

Table 4.5: Percentages of Inventory Contents in Waste Analysis.

Environmental Category	Inventory		Grand Total
	Inputs	Outputs	
Emission to air	61%	61%	61%
Emission to soil	8%	8%	8%
Emission to water	31%	31%	31%
Inventory indicator	0.01%	0.01%	0.01%
Unmapped flows	0.08%	0.08%	0.08%
Waste (as elementary flow)	0.00%	0.00%	0.00%
Grand Total	100.00%	100.00%	100.00%

Table 4.5 indicates that there is good reliability of the research results, the inputs match the outputs by 50% each for all classifications. It indicates good internal reliability of the research results, with the percentages of inputs and

outputs matching exactly across all environmental categories. This consistency suggests that the model is properly structured, maintains flow balance, and produces reproducible results.

Table 4.5 shows that air emissions represent 61%, soil emissions represent 8%, water emissions represent 31%, and the rest of the emissions represent less than 1%. This calls for the importance of focusing on air effects and what causes them.

One of the meanings of sensitivity is knowing the concentration of data and determining which data we care about. To know the concentration of influential data and which ones are more influential, select the [PivotTable tool], and select [number and percentage]. Table 4.5 shows the importance of the available elements.

Table 4.6 identifies the distribution of emissions (air, soil, water, inventory index, unmapped flows, and waste). This distribution shows a high concentration of elements in atmospheric emissions, accounting for 61% of the total. This suggests that the largest proportion, which causes all these impacts, should be focused on. This highlights the importance of air emissions. In the landfill scenario, air emissions account for -5%, meaning their impact is less than the value saved in the background system.

This can be explained by the fact that landfilling may mitigate climate change. The second impact is the release of water, which accounts for 31% of the waste's elemental content and affects each scenario to varying degrees. The third largest impact is emissions to soil, accounting for 8%, while the remaining emissions are very small, less than 1%.

Table 4.6: Distribution of Elements compared with different emissions by each scenario.

(E: Emission, II: Inventory Indicator, UF: Unmapped Flow, W: Waste (as elementary flow),

Impact	E to air	E to soil	E to water	II	UF	W	Grand Total
Elements	46370	5788	23530	8	62	2	75760
%	61%	8%	31%	0%	0%	0%	100%
AD	1.512	0.000	0.113	0.000	0.000	0.025	1.650
%AD	92%	0%	7%	0%	0%	2%	100%
C	0.201	0.000	0.018	0.000	0.000	0.025	0.244
%C	82%	0%	7%	0%	0%	10%	100%
G	1.360	0.000	0.018	0.000	0.000	0.025	1.403
%G	97%	0%	1%	0%	0%	2%	100%
I	-0.686	0.000	0.011	0.000	0.000	0.025	-0.650
%I	106%	0%	-2%	0%	0%	-4%	100%
L	-1.253	3.203	21.319	0.000	0.000	0.025	23.295
%L	-5%	14%	92%	0%	0%	0%	100%
R	1.190	0.000	0.495	0.000	0.000	0.025	1.710
%R	70%	0%	29%	0%	0%	1%	100%
SL	-0.075	0.000	-0.013	0.000	0.000	0.025	-0.062
%SL	120%	0%	20%	0%	0%	-40%	100%

4.3.2 Stage 3: LCIA

The charts below compare the results of testing different scenarios with indicators of environmental impacts. OpenLCA enables the selection of indicators of the ecological effects upon request, and at the end, it reviews the results together.

4.3.2.1 Climate Change

As illustrated in Figure 4.3, the landfill scenario has a big net contribution to climate change impact because it lacks a gas collection system and emits greenhouse gases, including CO₂, N₂O, and CH₄. In the sanitary landfill scenario, a clear enhancement is achieved regarding the net GWP by avoiding methane emissions. When landfill gas is composed as in the gasification scenario, fossil fuels and alternatives to oil shale-based electricity generation are saved. Therefore, improving the level of safe disposal of waste plays a major role in reducing the GWP compared with other scenarios. Composting, recycling, and incineration all lower waste production and greenhouse gas emissions, but their net effects on climate change vary. Recycling is the best use of waste, avoiding greenhouse gas emissions and helping achieve the SDGs of preserving natural resources for future generations.

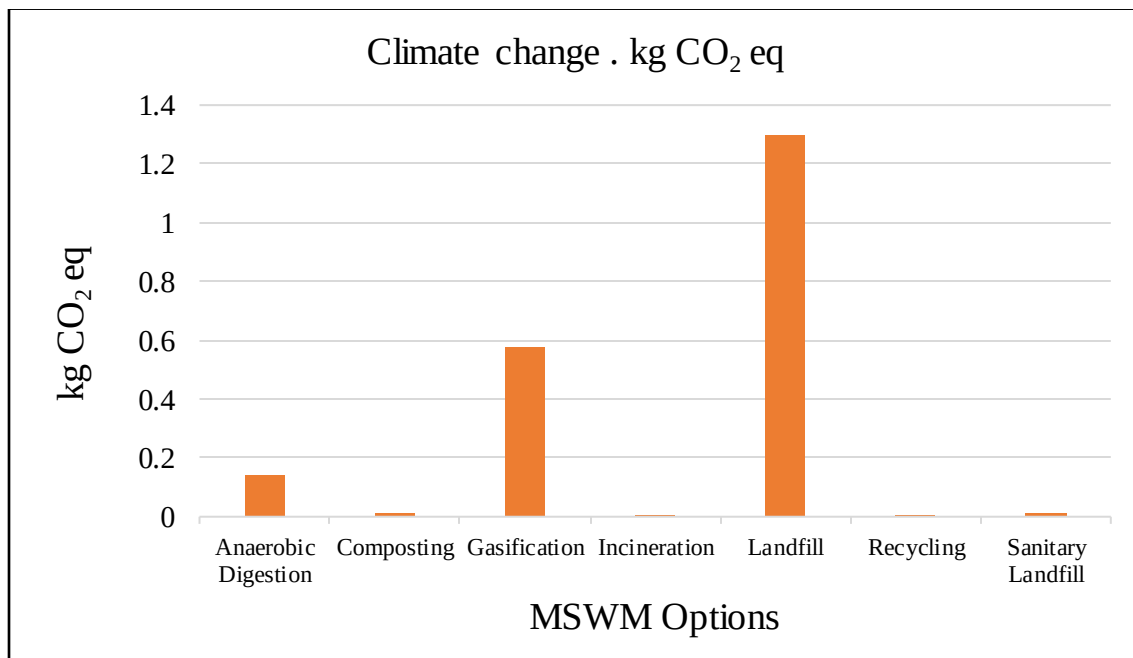


Figure 4.3: Climate Change of MSWM in Different Scenarios in Bahrain

Figure 4.3 illustrates the global warming potential (GWP) of the scenarios presented, with varying degrees of impact. The highest GWP is observed in the landfill scenario, followed by the gasification scenario, which comes in second place, and then the greenhouse effect scenario. Four scenarios (composting, incineration, recycling, and sanitary landfills) have lower levels, meaning they contribute less to the GWP. The emission of GHG, such as CH₄, CO₂, and N₂O, without collection, results in the anaerobic decomposition of organic waste from unsanitary landfills in Bahrain. In the landfill scenario, where a large amount of buried waste is present, this scenario negatively contributes to climate change. Landfills are a source of gas emissions, particularly methane, and can therefore be exploited to generate electricity by improving their management through more professional methods, such as the establishment of sanitary landfills to collect the gases. Landfill, gasification, and anaerobic digestion scenarios contribute to varying degrees to increasing the environmental impact in terms of GWP.

4.3.2.2 Terrestrial acidification

When the soil changes in chemical properties, acidification occurs after the deposition of nutrients such as nitrogen and sulfur in acidified forms. This study focuses on the effect of sulfur dioxide, which is one of the causes of soil acidification. Figure 4.4 shows the Terrestrial Acidification of the scenarios presented with different degrees of impact for each scenario. The highest terrestrial acidification rate is found in the anaerobic digestion scenario, followed by the gasification scenario in second place, then the composting and sanitary landfill scenario, while three scenarios (landfilling, incineration, and recycling) have a lower contribution and inversely, i.e., negative. Soil acidification can affect agricultural productivity if left untreated and thus the

sustainability of agricultural systems. Acidification seeps into the lower soil layers, affecting plant root growth and remedial measures.

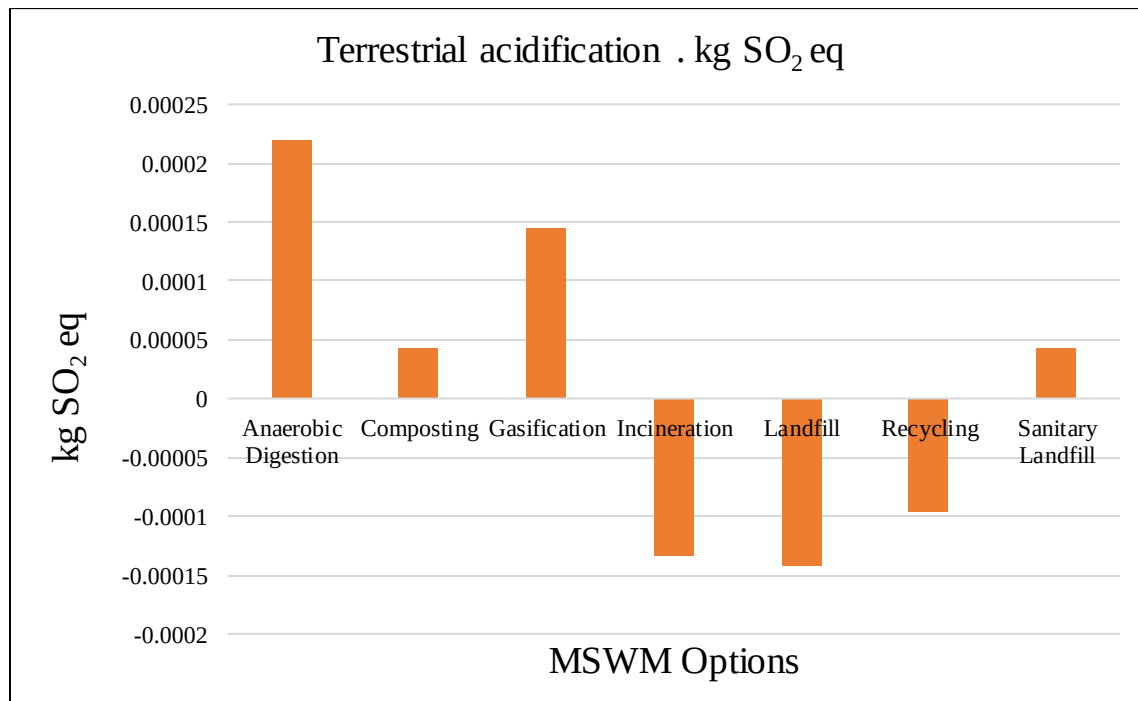


Figure 4.4: Terrestrial Acidification of MSWM in different scenarios in Bahrain.

4.3.2.3 Human toxicity

HTP stands for Human Toxicity Potential; it is a category used in LCA to evaluate the potential harm of toxic substances to human health. The highest HTP rate of all methods is found in the landfilling scenario at 0.034978 kg 1,4-DB eq as in Figure 4.5. The lowest HTP rate is in the incineration scenario, which reaches (-0.000301) kg. The other scenarios (composting, gasification, incineration, recycling, and sanitary landfill) are in the lowest level, which means that their contribution to HTP is less.

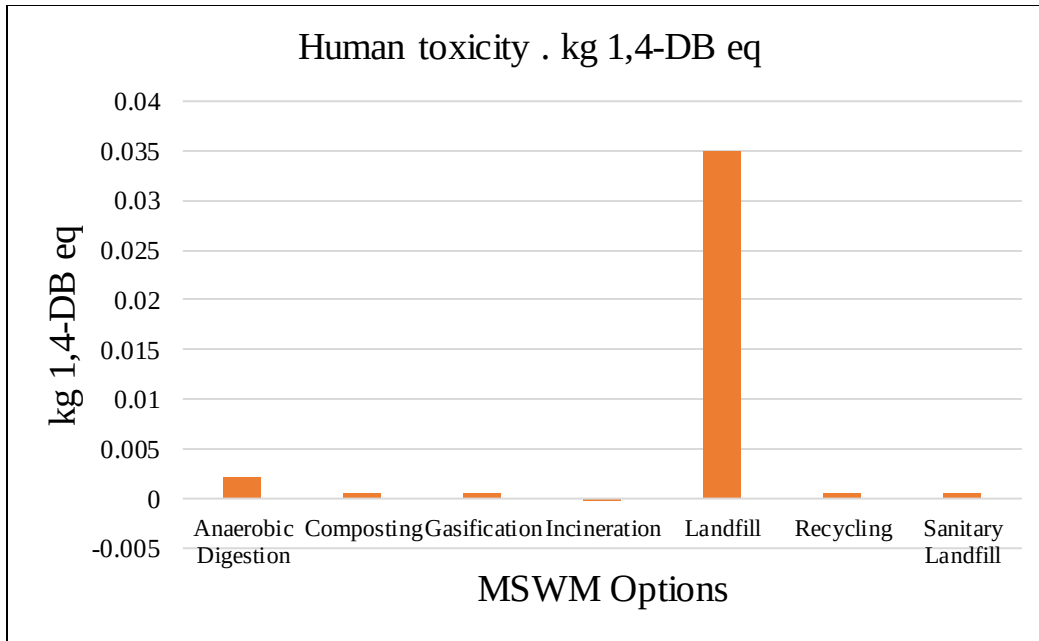


Figure 4.5: Human Toxicity of MSWM in Different Scenarios in Bahrain.

4.3.2.4 Freshwater Eutrophication

The impact of freshwater eutrophication category in each scenario adopted for the treatment of MSW varies to different degrees depending on the type of scenario. kg P eq stands for kilograms of phosphate equivalents, and it is a unit used in LCA to express the eutrophication potential of a product, process, or system. The potential for water eutrophication for the scenarios presented with different percentages of impact for each scenario (Figure 4.6). The highest rate of freshwater eutrophication is found in the landfilling scenario, followed by the AD, and the rest of the scenarios are found at lower levels with similar percentages, which means that their contribution to eutrophication is low. Landfill of waste, and anaerobic digestion contribute to increasing the environmental impact in terms of eutrophication to varying degrees.

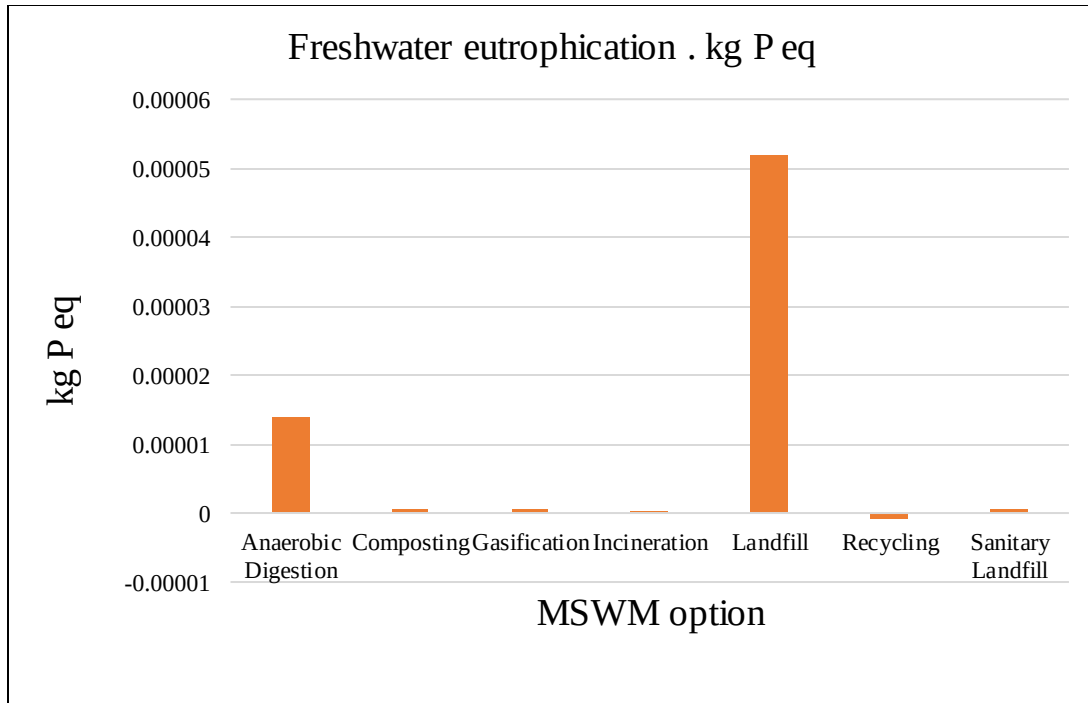


Figure 4.6: Freshwater eutrophication of MSWM in different Scenarios in Bahrain.

4.3.2.5 Urban Land Occupation

Figure 4.7 shows that the scenario values are positive except for one scenario, landfill, which has a negative value. Positive values indicate that urban land is being used in a way that depletes or consumes land resources. A landfill harms the sustainable use of the land it occupies. Negative values indicate a positive impact on urban land. This can occur when land is restored or reused in a way that benefits the environment or the urban community; this can enhance life quality and reduce pressure on urban land.

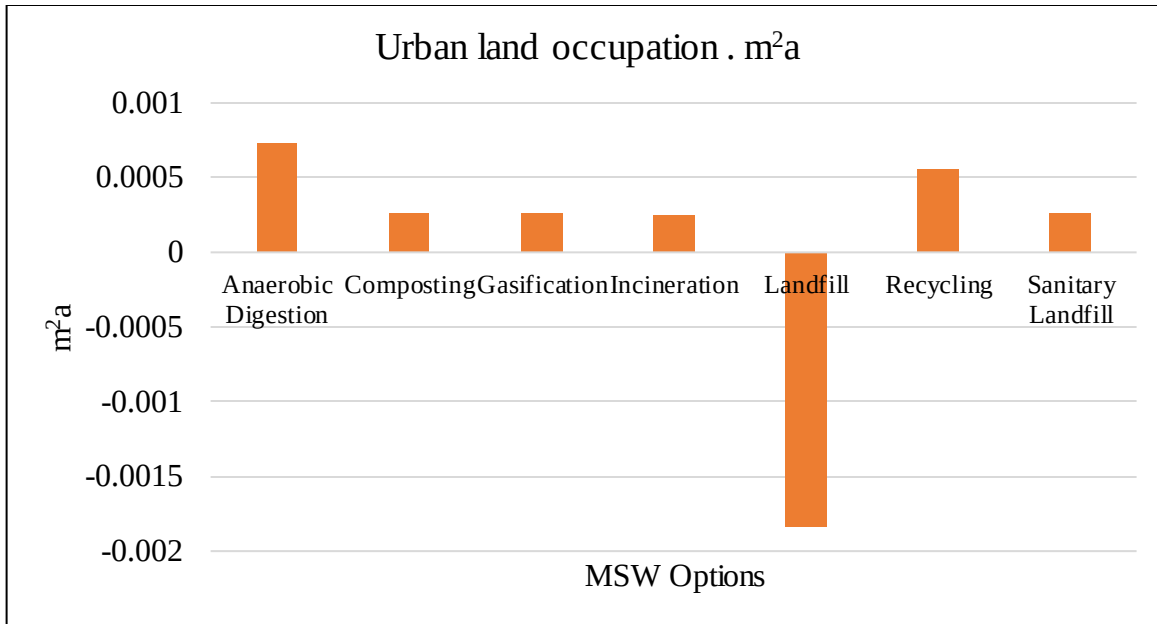


Figure 4.7: Urban land occupation of MSWM in different Scenarios in Bahrain.

4.3.2.6 Water depletion

Figure 4.8 shows the assessment of water depletion in waste management for each of the scenarios. The assessment of water depletion in different waste management technologies depends on the water use in each technology and its impact on water resources. In each scenario, there is water use in the waste treatment process and the amount of water varies depending on the water added. There is an impact on water depending on the liquids produced and the pollutants they contain that need to be treated. It is noted that anaerobic digestion has a negative value which means that water depletion is low, and water can be recycled within the system. In the composting process, moderate amounts of water are needed to maintain the moisture necessary to decompose organic matter. In this process, pollutants may be discharged into the soil, and depletion is limited. With careful moisture management, water depletion can

be reduced. Similarly, for both gasification and incineration, water discharge is low and is used for treatment or cooling water.

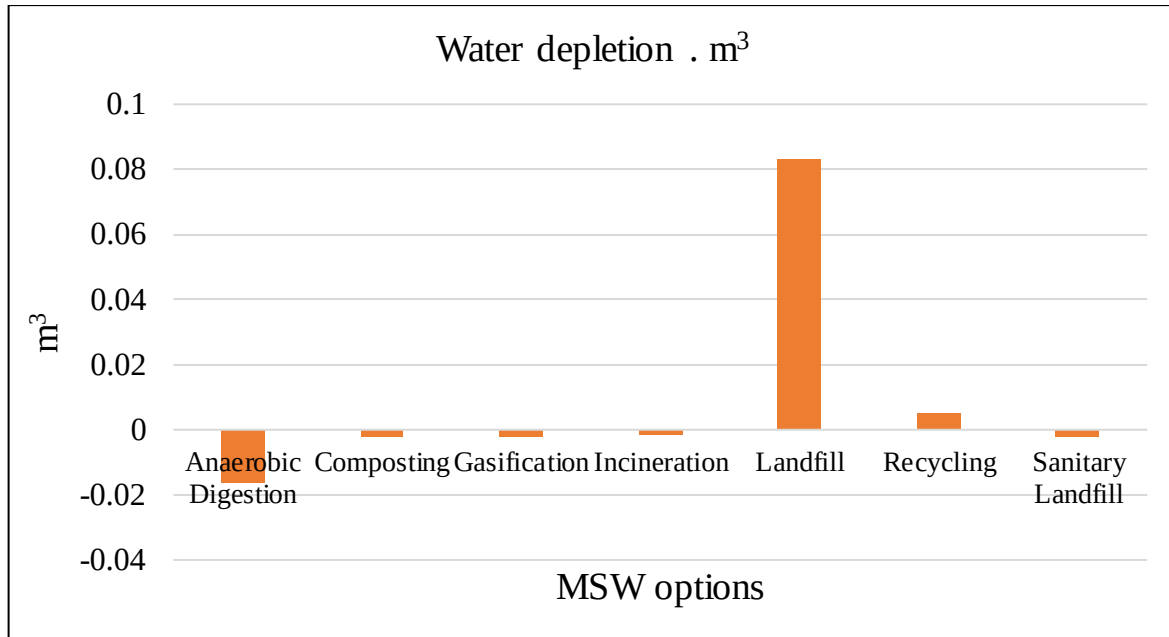


Figure 4.8: Water depletion on MSWM in different Scenarios in Bahrain.

In the landfilling process, water is not needed, but the waste produces liquids (leachate) that need to be treated, and groundwater sources can be polluted. In the waste recycling process, the process requires large amounts of water are required to wash the materials. This process contributes to the production of contaminated water before disposal. This process contributes to the depletion of water due to the recycled materials. As for the sanitary landfill process, it does not require large amounts of water and is characterized by a better fluid control system, which reduces the risk of groundwater contamination. Water depletion in this process is low. From Figure 4.8, it is noticed that positive values mean higher water depletion due to inefficient water use or the production of contaminated water that needs to be treated. Negative values

mean efficient use of water or recycling, which reduces the depletion of water resources.

4.3.3 Comparing all Scenarios with the Environmental Impacts

Comparing all the scenarios chosen as in Figure 4.9, it is noticed that the highest rate of environmental impacts in GWP is found in landfilling (1.296 kg CO₂ eq), gasification (0.578 kg CO₂ eq), and anaerobic digestion (0.143 kg CO₂ eq) scenarios, respectively.

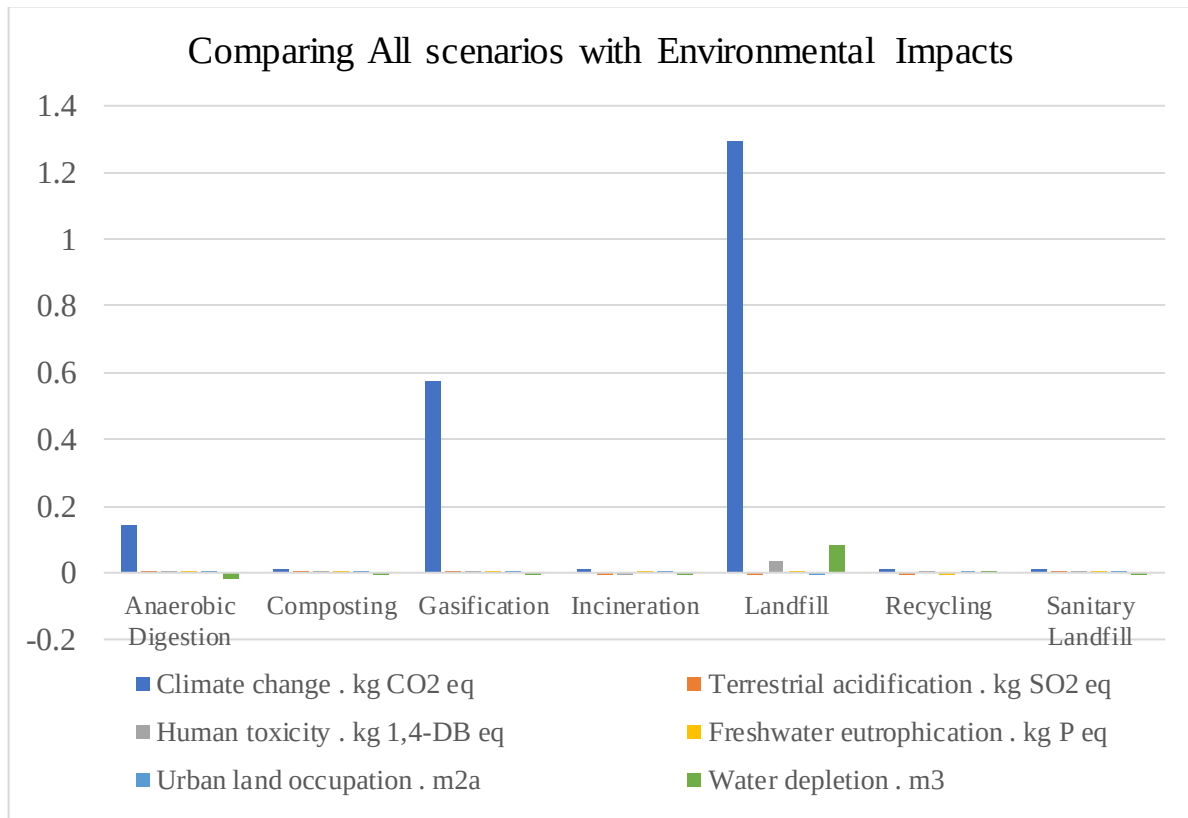


Figure 4.9: Comparing all scenarios with the environmental impacts.

4.3.4 Phase (4): Results Interpretation

There are negative environmental impacts from the scenario in place with landfills as a baseline, which could impact real-life situations if continued. Landfills in Bahrain lack engineering controls, and therefore, gases and leachate are not subject to control. Since gas emissions are released directly into the atmosphere, leachate can also enter groundwater.

4.3.5 Results of Environmental Impact in each Scenario

In Table 4.7, the red color indicates the highest impact while the green color indicates the lowest. The red color is concentrated in Landfilling and AD, while incineration and sanitary landfill recycling show the lowest impacts.

Table 4.7: Results of Environmental Impact in each Scenario.

(AD: Anaerobic Digestion- C: Composting- G: Gasification- I: Incineration- L: Landfill- R: Recycling- SL: Sanitary Landfill) (CC: Climate Change, TA: Terrestrial Acidification, HT: Human Toxicity, FE: Freshwater Eutrophication, UL: Urban Land, WD: Water Depletion) (IC: Impact Category)

IC	AD	C	G	I	L	R	SL
CC	0.14303	0.01159	0.57759	0.00835	1.29620	0.00903	0.00567
TA	0.00021	0.00004	0.00014	-0.00013	-0.00014	-0.00009	0.00001
HT	0.00225	0.00053	0.00053	-0.00030	0.03497	0.00049	0.00047
FE	0.00001	0.00001	0.00000	0.00001	0.00005	-0.00001	-0.00001
UL	0.00073	0.00026	0.00026	0.00025	-0.00183	0.00056	-0.00151
WD	-0.01646	-0.00199	-0.00199	-0.00174	0.08334	0.00517	0.00296

4.3.6 Ranking and Color Scales

Comparing the environmental impact scores of each scenario and ranking them by impact from highest to lowest gives the result as per Table 4.8. Excel tools (conditional formatting - color scales) were used to sort by color and numbering. Scenario 6 indicates the highest environmental impact, and 1 indicates the lowest environmental impact. To facilitate reading the table, a color scale was used. Red indicates the highest impact, green the lowest impact, while the rest of the results range in between.

Table 4.8: Ranking the environmental impacts of each scenario (descending order)

(AD: Anaerobic Digestion- C: Composting- G: Gasification- I: Incineration- L: Landfill- R: Recycling- SL: Sanitary Landfill) (CC: Climate Change, TA: Terrestrial Acidification, HT: Human Toxicity, FE: Freshwater Eutrophication, UL: Urban Land, WD: Water Depletion) (IC: Impact Category)

IC	AD	C	G	I	L	R	SL
CC	6	6	6	6	6	6	6
TA	3	3	3	3	2	1	3
HT	5	5	5	2	4	3	4
FE	2	2	2	4	3	2	2
UL	4	4	4	5	1	4	1
WD	1	1	1	1	5	5	5

Table 4.8 shows the ranking of environmental impacts for each scenario. It is obvious that the highest impact in all scenarios is climate change, which is affected by all scenarios. The anaerobic digestion scenario shows that the least impact is water depletion, followed by water eutrophication, then soil acidification, and urban land use comes in fourth place, followed by HTP in fifth place. A closer look at the table shows that the composting and gasification scenarios have the same impact as AD. However, the four scenarios (incineration, landfill, recycling, and sanitary landfill) differ in the ranking of environmental impacts in each scenario.

4.3.7 Comparing all Environmental Impacts with all Scenarios

Figure 4.10 shows that sanitary landfills and incineration perform best for climate change and human toxicity, while anaerobic digestion excels in water depletion but scores poorly in other areas. Composting leads in freshwater eutrophication, and landfiling ranks best only in terrestrial acidification and urban land use.

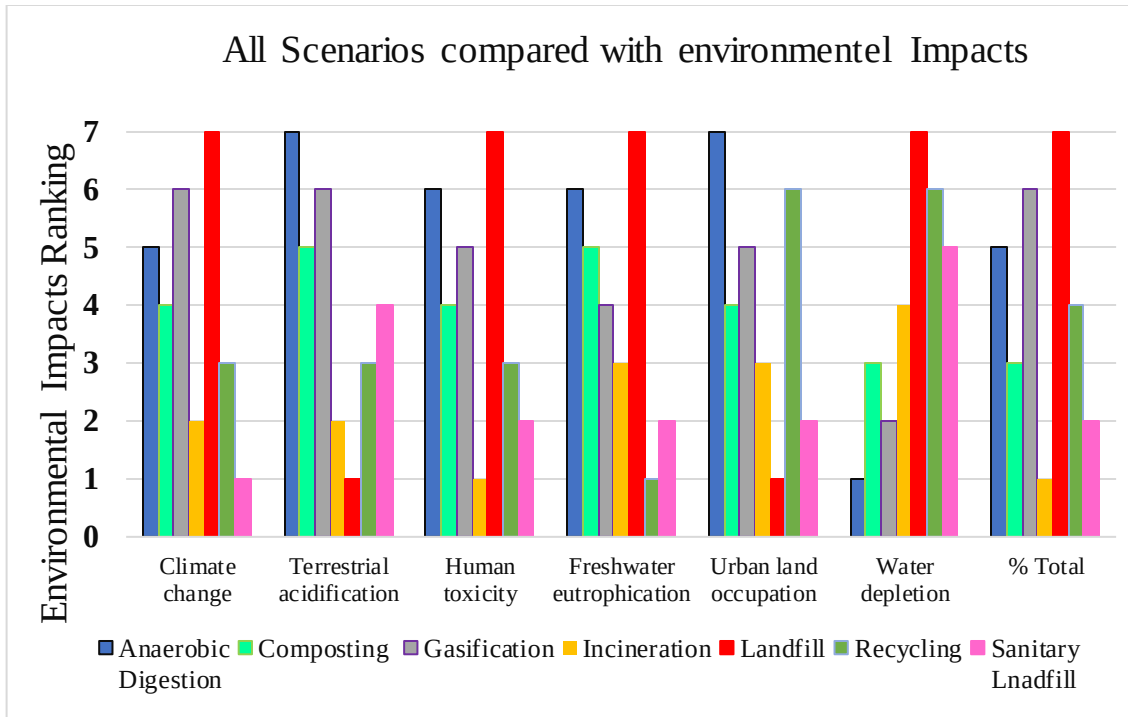


Figure 4.10: Comparing all environmental impacts with all scenarios (Using MS Excel).

Based on the comparison of the six environmental impact categories across all scenarios, the landfill scenario shows the highest impact in most categories. This indicates that, from an environmental perspective, using the LCA method, landfilling is the least sustainable option. Continued reliance on this method contributes significantly to environmental degradation and poses serious risks to human health.

4.3.8 Comparing all Scenarios with all Environmental Impacts

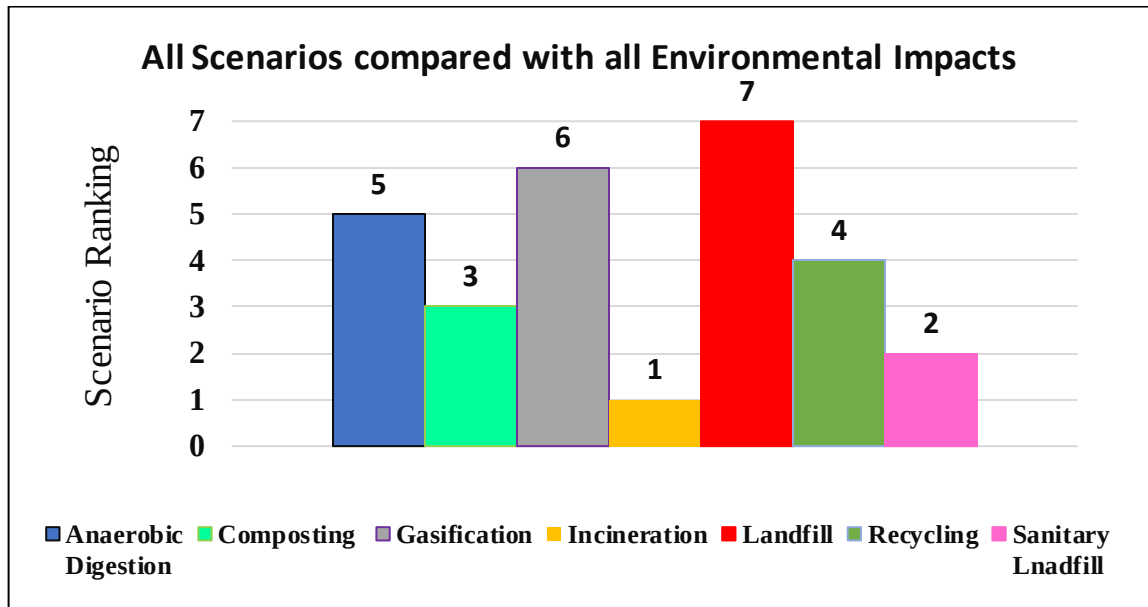


Figure 4.11: Comparing all scenarios with all Environmental Impacts (Using MS-Excel).

Figure 4.11 shows comparisons between the proposed scenarios with all selected environmental impacts. Landfills have the highest environmental impact, and the lowest environmental impacts of the tested environmental impacts are waste incineration, followed by sanitary landfill, composting, recycling, anaerobic digestion, and gasification scenarios, respectively. Open landfills were found to contribute more to climate change and HTP than sanitary landfills (Paul et al., 2024). In terms of environmental impacts, each scenario has its own comparisons as shown in the figure.

4.4 Awareness measurement

After distributing the questionnaire and collecting information, R-software, which is one of the famous software, and MS-Excel are used to analyze data. The following results were obtained.

4.4.1 Results of pilot study

The survey data was analyzed, and the results were as follows:

Table 4.9: Mean and Standard deviation in pilot study

Field	Mean	Standard Deviation
Attitude	3.8	1.2
Knowledge	3.8	1.3
Practice	3.5	1.1
Grand Total	3.7	1.2

The overall KAP scores are a mean of 3.7 and a standard deviation of 1.2, as in Table 4.9. The purpose of these calculations and analyses is to examine the degree of robustness of the survey questionnaire results. The correlation coefficient was calculated to be 0.87, which means a strong correlation. The reliability coefficient is equal to 0.93, which means it is very high. The sum of the variances is 27.3, and the total variance is 199, giving us a Cronbach's Alpha coefficient of 0.9, which means high reliability for the survey.

4.4.2 Questionnaire Results and Discussion

This section reviews the results, analyzes them, obtains a summary, interprets them, and writes a conclusion that answers the research questions and achieves its objectives.

4.4.3 Data description

The dataset includes 37 variables and 1,059 cases with no missing data, summarized in Table 4.10. Data were collected using R software and cover key demographic characteristics—age, language, gender, marital status, housing type, and household size—essential for analyzing behavioral patterns in the study. Participants were surveyed over 21 days (Aug 9–31, 2024), helping to reduce timing bias. Most participants spoke Arabic (89.6%) and were aged between 41 and 60 (60.7%), indicating a mature and stable demographic group. Men constituted 67.1% of the sample. A high level of education was observed, with 77.9% holding at least a university degree. Most were married (86.2%) and Bahraini nationals (95.1%), with the majority from the Northern Governorate (58.1%). Public and private sector employees were well represented. The majority belong to middle-income households (BD 301–900), lived in single-family homes (73%), and have 3–5 family members (50.9%). These insights support the design of policies tailored to age, income, and housing characteristics while identifying demographic gaps.

Table 4.10: Demographic description (R software)

Sr.	Variable	Stats / Values	Freqs (% of Valid)
1.	Timestamp	min: 2024-08-09 20:07:47.119 med: 2024-08-13 16:13:37.195 max: 2024-08-31 00:48:41.922 range: 21d 4H 40M 54.8S	1059 distinct values
2.	language	1. Arabic 2. English	949 (89.6%) 110 (10.4%)
3.	Age	1. 18-20 years 2. 21-30 years 3. 31-40 years 4. 41-50 years 5. 51-60 years 6. 61 and above	13 (1.2%) 95 (9.0%) 207 (19.5%) 369 (34.8%) 274 (25.9%) 101 (9.5%)
4.	Gender	1. Female 2. Male	348 (32.9%) 711 (67.1%)
5.	Educational Level	1. Intermediate and below 2. Postgraduate 3. Secondary 4. Undergraduate	10 (0.9%) 265 (25.0%) 224 (21.2%) 560 (52.9%)
6.	Marital Status	1. Married 2. Other 3. Single	913 (86.2%) 29 (2.7%) 117 (11.0%)
7.	Nationality	1. Bahraini 2. Non-Bahraini	1007 (95.1%) 52 (4.9%)
8.	Area of Living	1. Capital Governorate 2. Muharraq Governorate 3. Northern Governorate 4. Southern Governorate	242 (22.9%) 84 (7.9%) 615 (58.1%) 118 (11.1%)
9.	Occupation	1. Government 2. Housewife 3. Other	402 (38.0%) 38 (3.6%) 19 (1.8%)

Sr.	Variable	Stats / Values	Freqs (% of Valid)
		4. Private Sector 5. Retired 6. Semi-Government 7. Unemployed	355 (33.5%) 155 (14.6%) 53 (5.0%) 37 (3.5%)
10.	Monthly Family Income	1. BD 1501 and above 2. BD 300 and below 3. BD 301-900 4. BD 901-1500	243 (22.9%) 116 (11.0%) 403 (38.1%) 297 (28.0%)
11.	Number Of Family Members	1. 1 or 2 persons 2. 3-5 persons 3. 6-8 persons 4. 9 persons and above	121 (11.4%) 539 (50.9%) 362 (34.2%) 37 (3.5%)
12.	Place of Residence Type	1. Flat 2. House	286 (27.0%) 773 (73.0%)

The data in Table 4.11 provides a clear social overview of public awareness, attitudes, and behaviors related to household waste management. The majority of respondents demonstrated strong knowledge of key environmental concepts, with over 87% understanding the meaning of waste segregation and over 91% familiar with recycling. General attitudes were overwhelmingly positive, with 96% agreeing that proper segregation and recycling are good for the environment, and nearly 90% recognizing the economic benefits. There is also strong support for government action, with 77% supporting the enactment laws mandating waste segregation at the source, and over two-thirds support gradual enforcement. In terms of behavioral intention, nearly 80% expressed readiness to segregate waste at home if municipalities provide appropriate infrastructure, and over 80% are willing to cooperate with

awareness or civil society-led programs. Furthermore, 75% support integrating technology into waste management.

However, the analysis reveals a gap between knowledge and daily practices. While awareness is high, only about 54% reported actively practicing segregation at home, and 32% still do not use eco-friendly shopping bags. Similarly, almost 20% continue to use plastic despite acknowledging its harmful effects. Satisfaction with current waste management services is relatively low, with only 37% expressing approval, and just a third of them consider current systems to be environmentally friendly. Education is seen as a critical tool, with 93% supporting the inclusion of waste management in school curricula and media. Regarding financial participation, public opinion is divided, with more than half rejecting the idea of paying additional fees for improved services. Overall, the community demonstrates high environmental literacy, strong policy support, and willingness to change—yet to fully achieve sustainable outcomes, service improvements, accessible infrastructure, and behavioral incentives are needed to bridge the gap between intention and practice.

Values are: (1) Not true at all or Strongly Disagree - (2) Not True/ Disagree - (3) Not Sure/ Not Sure - (4) True/ Agree - (5) Totally True/ Strongly Agree.

Table 4.11: Variable description (R software)

Sr.	Variable	1		2		3		4		5	
		Fr	%	Fr	%	Fr	%	Fr	%	Fr	%
1.	I know that there is a law regulating waste management in the country	47	4.4	82	7.7	381	36	292	27.6	257	24.3

2.	I know the meaning of “waste segregation”	5	0.5	19	1.8	106	10	392	37	537	50.7
3.	I know the meaning of “waste recycling”	3	0.3	7	0.7	69	6.5	389	36.7	591	55.8
4.	I know the meaning of “organic waste”	14	1.3	46	4.3	239	22.6	353	33.3	407	38.4
5.	The process of segregating and recycling waste in the right way benefits state economy	1	0.1	8	0.8	102	9.6	328	31.0	620	58.5
6.	The process of segregating and recycling waste in the right way benefits the environment	3	0.3	4	0.4	36	3.4	265	25	751	70.9
7.	I think it is important for the government to enact a law that obliges the process of segregation of waste sources	25	2.4	46	4.3	173	16.3	342	32.3	473	44.7
8.	I am satisfied with the performance of Household Waste Management in the country	101	9.5	198	18.7	364	34.4	274	25.9	122	11.5
9.	I am ready to segregate the waste at home if the municipalities request it and provide separate bins/skips to collect waste according to the type	14	1.3	34	3.2	166	15.7	401	37.9	444	41.9

10.	I support the idea of deploying containers to collect the recyclable wastes in residential neighborhoods	7	0.7	6	0.6	35	3.3	378	35.7	633	59.8
11.	Waste management is a shared responsibility between regulatory authorities and all members of society	5	0.5	13	1.2	54	5.1	359	33.9	628	59.3
12.	I favor charging an additional fee for better management of household waste	298	28.1	294	27.8	236	22.3	124	11.7	107	10.1
13.	The importance of household waste management shall be included in the educational curriculum and published through various media sources	5	0.5	11	1	60	5.7	376	35.5	607	57.3
14.	I am ready to cooperate with a program that contributes to awareness of the management of household waste	9	0.8	18	1.7	177	16.7	437	41.3	418	39.5
15.	I am ready to cooperate with a project led by civil society organizations to sustain waste management	10	0.9	15	1.4	169	16	456	43.1	409	38.6

16.	The current method of collecting household waste is considered an environmentally friendly one	104	9.8	217	20.5	384	36.3	227	21.4	127	12
17.	I support the state's gradual enforcement of the mandatory segregation of waste at the sources	55	5.2	77	7.3	199	18.8	407	38.4	321	30.3
18.	I support the use of technology in the management of household waste	8	0.8	20	1.9	116	11	413	39	502	47.4
19.	I advise others to put the residues in their proper places	45	4.2	75	7.1	135	12.7	402	38	402	38
20.	I practice segregating household waste at home, such as food, plastic, glass, and paper	128	12.1	209	19.7	146	13.8	403	38.1	173	16.3
21.	I use multipurpose, environmentally friendly water bottles	56	5.3	128	12.1	154	14.5	425	40.1	296	28
22.	I consume less plastic because of its harmful effects on the environment	72	6.8	134	12.7	191	18	435	41.1	227	21.4
23.	I contribute to spreading environmental awareness in the community whenever I have the opportunity	43	4.1	117	11	169	16	441	41.6	289	27.3

24.	I use multipurpose, eco-friendly shopping bags	122	11.5	181	17.1	196	18.5	331	31.3	229	21.6
25.	I follow municipal regulations regarding the disposal of household waste	35	3.3	50	4.7	171	16.1	337	31.8	466	44

4.4.4 Statistical concepts and tools

This is a summary of the explanation of some statistics.

4.4.4.1 Structural Equation Modelling

Structural Equation Modelling (SEM) has been used to analyze the questionnaire data. SEM is a multivariate quantitative method used to characterize the connections between observable variables called structural equation modeling, or SEM (Thakkar, J. J., 2020).

4.4.4.2 Regression Coefficient

The Regression Coefficient (represented by EST) is a statistical measure to calculate the average functional relationship between variables. It can also be used to measure the degree of dependence of one variable on another. In regression analysis, one variable is dependent, and the other is independent (Field, A., 2018).

4.4.4.3 Effect size

Effect size is a number that indicates the degree to which a particular variable affects another variable, describing its effect as small, medium, or large (Ellis P. D., 2010). It is the difference between the means and measures whether there is a significant difference between the variables.

4.4.4.4 Meaning of Significant

Statistical Significance is established when the p-value is very small. Statisticians often say the effect is statistically significant when the p-value is 0.05 or less. This does not mean that the effect has practical importance because we can get a statistically significant result of a very low magnitude that has no practical value (Ellis P. D., 2010).

4.4.4.5 Correlation Matrix of predictor variables

To measure the strength and direction of the relationship between two variables, a statistical measure called correlation is used (Moore et al., 2012). The range is from -1 to +1, (+1) indicates a perfect positive, which means a constant relationship between the variables, while (-1) indicates a perfect negative and an inverse relationship between the variables (Field, A., 2018).

4.4.4.6 Confirmatory Factor Analysis

Confirmatory Factor Analysis (CFA) is a sophisticated statistical technique used to verify the factor structure of a set of observed variables. It allows researchers to test the hypothesis that a relationship exists between observed variables and their underlying latent constructs.

Before going further, the data were inspected for multicollinearity. When multicollinearity exists between indicators, there will be an overlap of latent constructs. This makes it difficult to distinguish the individual contributions of each indicator. This overlap can distort estimates and amplify errors, which reduces the interpretability and validity of the model (Brown, T. A., 2015; Kline, R. B., 2023).

Figure 4.12 shows a graphical representation of the correlation matrix for all variables (25) used for measuring the latent variables. By examining the matrix, it is noted that the variables a6 and a7 are highly correlated. So, one of them can be eliminated from the analysis (Kline, R. B., 2023). In this step, the researcher does not make a formal statistical test but inspects the correlation matrix to remove highly correlated variables.

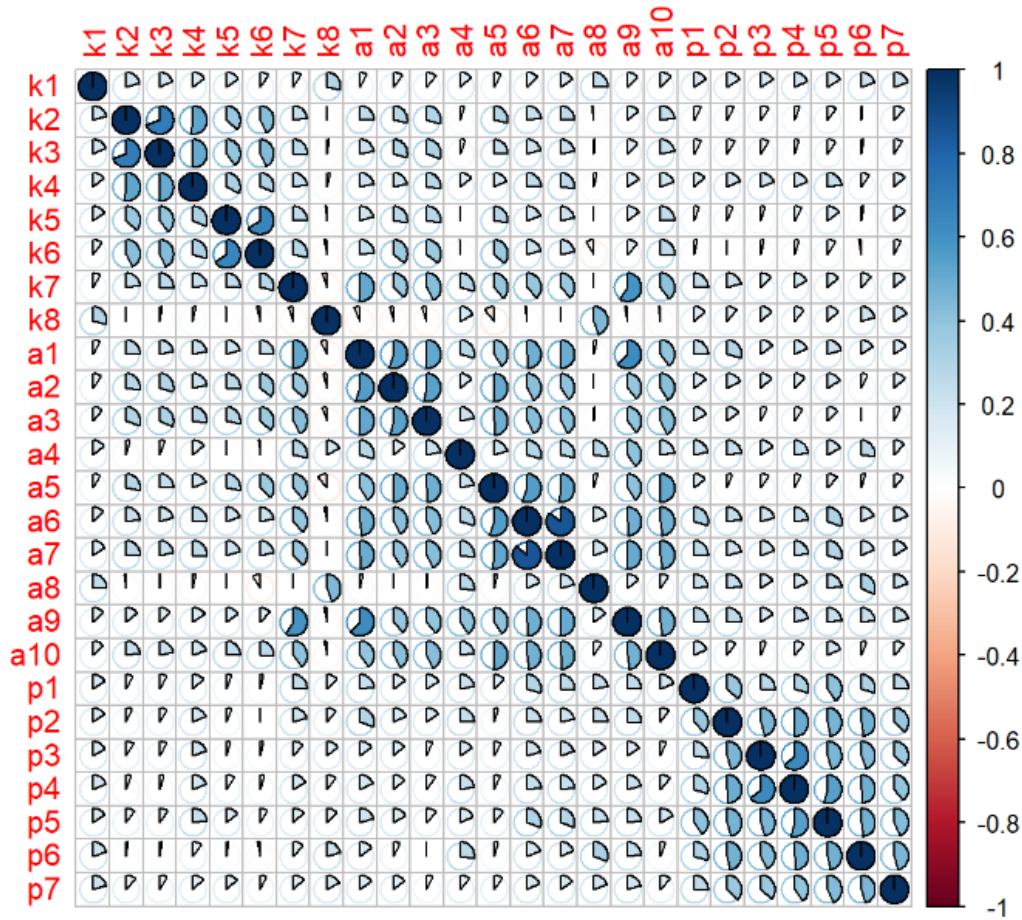


Figure 4.12: Correlation Matrix (Collinearity graph for the variables measuring the main study constructs).

After the multicollinearity analysis, CFA has been conducted. Figure 4.13 describes the output of CFA. The square shape means the variable that is

measured and is something tangible and called a manifest variable, while the oval shape means an intangible variable and is called a latent variable. The correlation between the KAP variables is 0.14, 0.06, and 0.15, respectively. This indicates that there is no correlation between knowledge, attitude, and practice. Therefore, it cannot be said that there is a linear direct relationship between these variables.

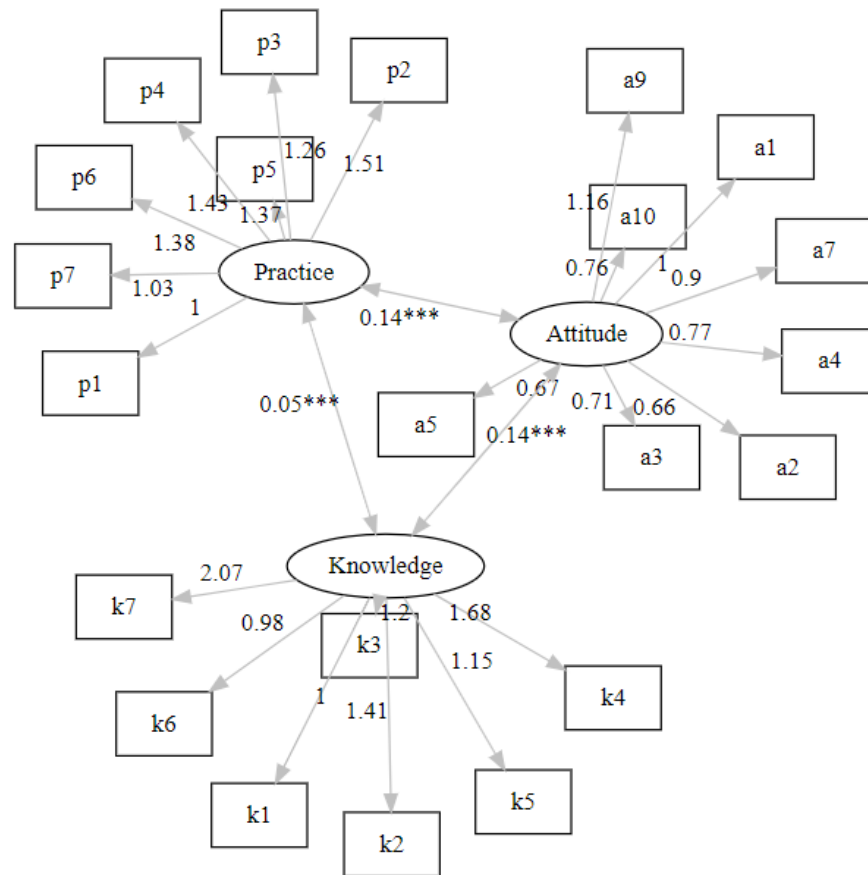


Figure 4.13: CFA Model for KAP (R-software)

4.4.4.7 Assessing Model Fit

Assessing model fit is important to check the performance of the whole model and ensure that it represents the data well. There are common methods and

metrics for evaluating model fit in different types of models. The Model fit can be assessed by various numerical figures called “Fit Indices”. Table 4.12 shows the values of Model indices (indexes).

Table 4.12: Fit Indices for assessing model fit.

Index Name	Value	Explanation
Chi-sq	1216.79	Chi-square goodness of fit test
Df	206	Degrees of freedom of the chi-square
P-value	0	It is the probability of obtaining test results at least as extreme as the result actually observed, under the assumption that the null hypothesis is correct
CFI	0.919	Comparative fit index
TLI	0.909	Tucker–Lewis’s index
RMSEA	0.068	root mean square error of approximation
SRMR	0.08	Standardized Root Mean Square Residual

The first fit index is the chi-square test statistic. The null hypothesis (H_0) of the chi-square test is that the Population Covariance Matrix equals the Covariance Matrix implied by the model. The p-value of the chi-square test < 0.001 suggests that the Model does not fit the data, but this finding should be ignored because it is well-known that the chi-square test is sensitive to large samples (Finch & French, 2015). Next, the CFI (Comparative Fit Index) and

TLI (Tucker-Lewis's index) fit indices, values of these indices are 0.919 and 0.909, respectively. Both are close to 0.90, suggesting an adequate fit, as shown in Table 4.13. The RMSEA (Root mean square error of approximation) has a value of 0.068, which is less than the cut value of 0.08, suggesting a good fit (Kline, R. B., 2023).

Table 4.13: Fit Index types (Keith, T. Z., 2019)

<i>Fit Index</i>	<i>May be useful for & other notes</i>	<i>Common criteria</i>
χ^2	Useful as stand-alone measure with $N = 75$ to 400. Tested for statistical significance with df	non-significance supports the model
$\Delta\chi^2$	Comparing competing, nested models, $N \leq 1000$	Non-significance supports the model with larger df ; significance supports the model with smaller df
RMSEA	Stand-alone measure of fit. Can calculate confidence intervals around RMSEA, and test whether an obtained RSMEA is statistically significantly different from some value (e.g., .05)	$\leq .05$ = good fit (close fit) $\leq .08$ = adequate fit $\geq .10$ = poor fit
SRMR	Stand-alone measure of fit. Intuitively appealing	$\leq .08$ = good fit, although $\leq .06$ may be a better criterion
CFI	Stand-alone measure of fit. Some research suggests ΔCFI may be useful in invariance testing (see Chapter 19)	$\geq .95$ = good fit $\geq .90$ = adequate fit
TLI	Stand-alone measure of fit	$\geq .95$ = good fit $\geq .90$ = adequate fit
AIC	Comparing competing models—nested or non-nested	Smaller is better
BIC	Same as AIC, but larger reward for parsimony	Smaller is better
aBIC	Same as AIC, in between AIC and BIC in reward for parsimony	Smaller is better

SRMR (Standardized root mean square residual) equals 0.08, equal to the cut value of 0.08, suggesting a good fit to the data. Therefore, taking all fit indices together, it can be concluded that the model adequately fits the data. In the section below, demographic variables are added to the model to see if they affect the latent variable KAP. If the first fit is bad, there is no need to check the rest, but if the first fit is good, we can build on it and continue, and do SEM. According to Finch and French (2015), the cut-point is a value that, when a fit index is above or below it, it can be concluded that the model fits the data very well.

4.4.5 Effect of Demographic Variables on Latent Variable

Since the study uses latent variables, instead of using a T-test and ANOVA, several SEM models have been run to study the effect of each demographic variable on the KAP latent variables.

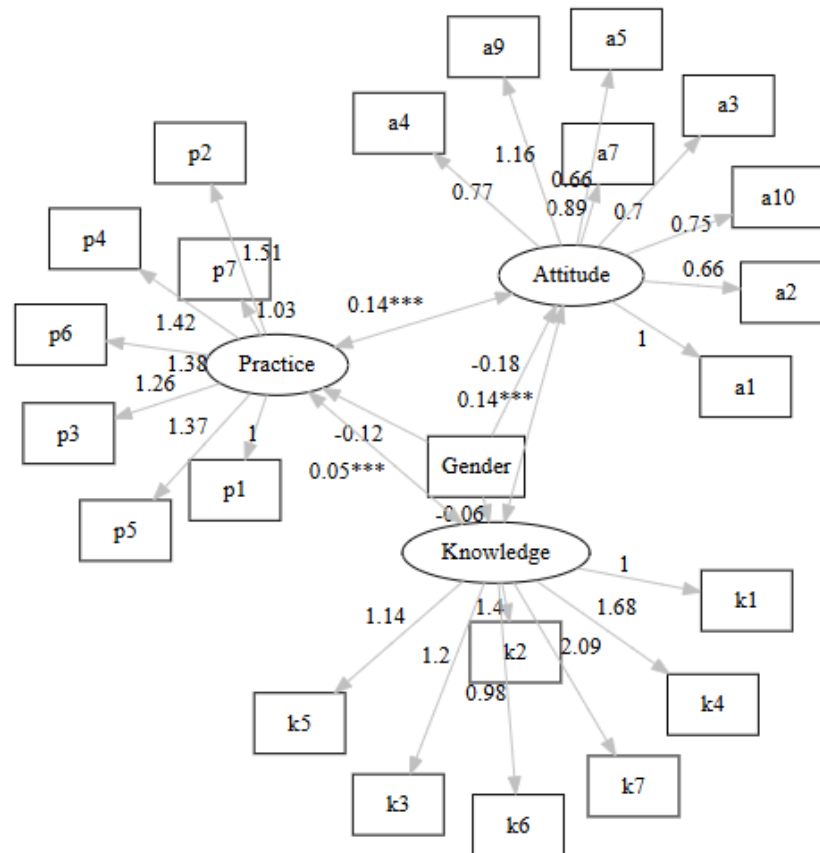


Figure 4.14: SEM output of gender effect in latent variable.

Figure 4.14 shows the structural equation model (SEM) used to analyze the relationships between latent variables such as knowledge, attitude, and practice, as well as the effect of gender on them. The arrows pointing into the boxes represent the relationship between the latent variable and the indicators. For example, the arrow from attitude to a7 has a value of 0.89, meaning that a7 explains 89% of the variance in attitude, or vice versa. The symbol *** indicates high statistical significance ($p < 0.001$). Attitude has a positive and significant effect on practice (0.14*): **. The more positive individuals' attitudes are, the more likely they are to implement sound practices. Although knowledge is essential, its direct effect on behavior (practice) was insignificant. The strongest factor influencing practice is attitude, not

knowledge. Gender has a significant but relatively weak effect. Some items such as a7, p1, and k2 have high loading coefficients, meaning they strongly represent the latent variable.

Table 4.14: Effect of All Demographic Variables on Latent Variable

Parameter	Gender	Age	Education	Occupation	Income
CHI-SQ	1242.775	1242.78	1702.95	2421.06	1238.04
DF	225	225	245	266	225
P-VALUE	0	0	0	0	0
CFI	0.919	0.919	0.888	0.827	0.92
TLI	0.909	0.909	0.874	0.805	0.91
R-MSEA	0.065	0.065	0.075	0.092	0.065
S-RMR	0.077	0.077	0.081	0.085	0.077
Interpretation	Good fit	Good fit	Poor fit	Poor fit	Adequate Fit

Table 4.14 presents the results of an SEM to assess the effect of demographic variables (gender, age, education, occupation, income) on a latent variable, a variable that is not directly observed but is measured through multiple indicators (such as knowledge, attitudes, or practices in waste management). The CHI-SQ is used to test the model's goodness of fit. High values do not always mean poor but should be interpreted in conjunction with the other indicators. DF (Degrees of Freedom) are the degrees of freedom associated with the model. In P-VALUE, all values are considered to be 0 (less than 0.05), indicating that the models are statistically significant, but on their own, they are not sufficient to determine goodness of fit. The CFI (Comparative Fit

Index) is a comparative goodness of fit index; a value of ≥ 0.90 indicates a good fit. The TLI (Tucker-Lewis Index) is another indicator of model goodness of fit; a value of ≥ 0.90 indicates a good fit. RMSEA (Root Mean Square Error of Approximation) values between 0.05 and 0.08 are considered good, and values above 0.08 are considered poor. SRMR (Standardized Root Mean Square Residual) values should be ≤ 0.08 to indicate a good fit.

This table shows that the effects of gender and age on the latent variable can be reliably assessed because they rely on well-fitting models. The effects of education and occupation suffer from poor model fit and may require reworking or testing alternative models. Income has a moderate model fit, and its results can be used with caution.

4.4.6 Abbreviations of variables:

LHS: *Left-Hand Side*: It is the dependent variable (what you are trying to predict or model).

RHS: *Right-Hand Side*: This refers to the independent variables (predictors or features).

EST: *Estimate*: It refers to the estimated coefficient for a variable in regression models.

Table 4.15: Parameter Estimates for all Demographics Model

LHS	RHS	STD.ALL	EST	Interpretation
Knowledge	Gender	-0.091	-0.062	Very low effect

LHS	RHS	STD.ALL	EST	Interpretation
Attitude	Gender	-0.129	-0.18	
Practice	Gender	-0.096	-0.12	
Knowledge	Age	0.038	0.001	weak
Attitude	Age	0.021	0.001	
Practice	Age	0.093	0.005	
Knowledge	E1	-0.049	-0.038	No effect
Knowledge	E2	-0.055	-0.036	
Attitude	E1	0.017	0.027	
Attitude	E2	-0.075	-0.099	
Practice	E1	0.107	0.152	
Practice	E2	-0.100	-0.118	
Knowledge	O1	0.083	0.055	No effect
Knowledge	O2	-0.147	-0.099	
Knowledge	O3	0.039	0.034	
Attitude	O1	-0.004	-0.005	

LHS	RHS	STD.ALL	EST	Interpretation
Attitude	O2	-0.033	-0.045	
Attitude	O3	0.041	0.073	
Practice	O1	-0.088	-0.102	
Practice	O2	0.059	0.070	
Practice	O3	0.018	0.028	
Knowledge	I	0.146	0.031	Moderate
Attitude	I	0.085	0.038	
Practice	I	-0.047	-0.018	

EST represents the regression coefficients of each demographic variable on Knowledge, Attitude, and Practice. The demographic variables are coded on a 1–5 scale, so each regression coefficient (EST) represents the change in the outcome associated with a one-unit increase in the demographic score. The estimated effect is described as in the interpretation column in Table 4.15.

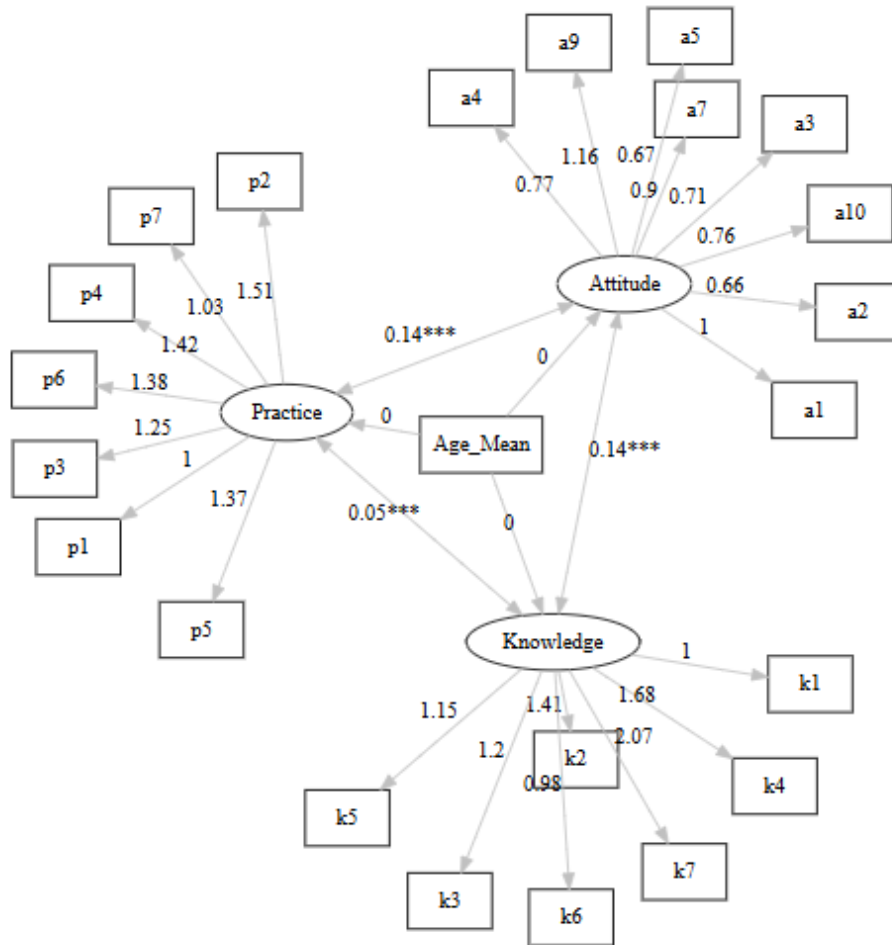


Figure 4.15: SEM output of Age Effect in Latent Variable (from R-Software).

Figure 4.15 shows the SEM used to analyze the relationships between latent variables as well as the influence of gender on them. It displays the relationships between latent variables with the inclusion of an exogenous variable, age mean. It can be concluded from this figure that attitude positively influences practice, indicating the importance of adopting positive attitudes toward waste management or any sustainable behavior. Knowledge increases with age, indicating that older adults possess greater knowledge in this area. Age has a minor effect on practice, perhaps due to accumulated experience.

Age does not affect attitude, meaning that attitudes are not directly related to age but rather to other factors such as education or culture.

Table 4.16: Correlation Coefficient.

Correlation	Knowledge	Attitude	Practice
Knowledge	1.0	0.655	0.279
Attitude	~	1.0	0.362
Practice	~	~	1.0

Table 4.16 shows the correlation coefficients between three variables: Knowledge, Attitude, and Practice. It is a correlation matrix, where each value represents the Pearson correlation coefficient (r) between two variables. Knowledge and Attitude ($r = 0.655$) have a strong positive correlation. As knowledge increases, attitude tends to improve significantly. Knowledge and practice ($r = 0.279$) have a weak to moderate positive correlation. More knowledge may lead to better practices, but not strongly. Attitude and practice ($r = 0.362$) moderate positive correlation. Better attitudes are somewhat linked with better practices.

4.4.7 Summary of the questionnaire

By analyzing the questionnaire data using CFA and SEM, there is no relationship between individual characteristics and the three variables KAP. When using CFA and SEM, there is a lack of relationship between individual characteristics (such as age, gender, and education level) and the three variables of KAP. This indicates that demographic characteristics are not influential factors on these variables in the context of the studied sample. This

results in the individual-specific variables not explaining the variance in levels related to KAP, and the effect may be due to other factors such as environmental awareness, personal values, or socio-economic factors. To achieve effective social sustainability in waste management, it is recommended to enhance cooperation between civil society, local authorities, and educational institutions to implement sustainable and comprehensive programs.

The study of Tran, T. T. (2018) suggests that obtaining environmental knowledge, especially regarding waste and proper recycling, can improve an individual's recycling behavior. The researcher's experiment shows that those who were more exposed to different sources of environmental information about recycling were more likely to do so than those who were less exposed. Providing information about waste and recycling was also shown to improve individual recycling behavior. The results of the study by Le Tan and Dai Trang (2017) show that there is a difference between males and females in knowledge sharing and that males tend to share knowledge more than females. The weak relationship between the variables may be due to hidden factors that were not included in the analytical model and affect those variables. Yepes and López (2023) found that multiple factors, such as information and communication technologies as well as organizational innovation climate, play a role in the richness of creative behavior.

Saitoh et al., (2022) revealed that there is a significant negative relationship between the rate of household waste generation and the number of household population and a significant positive relationship between the average age of the household and income. Utilizing resident leaders is cost-effective in positively influencing waste management awareness (Saitoh et al., 2022).

4.4.8 KAP Measurement

The proportions of each of KAP are estimated by adding the percentages of agreement and strong agreement from the questions of each axis (8, 10, and 7) for all respondents, as follows:

Knowledge= K1 (28% + 24%) + K2 (37%+51%) + K3 (37% + 56%) + K4 (33%+ 38%) + K5 (31% + 59%) + K6 (25%+ 71%) + K7 (32% + 45%) + K8 (26% + 12%) = 605%/8 =75.6%

Attitude= A1 (38% +42%) + A2 (36%+60%) + A3 (34%+59%) + A4 (12%+10%) + A5 (36%+57%) + A6 (41%+39%) + A7 (43%+39%) + A8 (21%+12%) + A9 (38%+30%) + A10 (39%+47%) = 734%/10 =73.4%

Practice= P1(38%+38%) + P2 (38%+16%) + P3(40%+28 %) + P4(41%+21%) + P5(42%+27%) + P6 (31%+22%) + P7(32%+44%) =459%/7 =65.5%

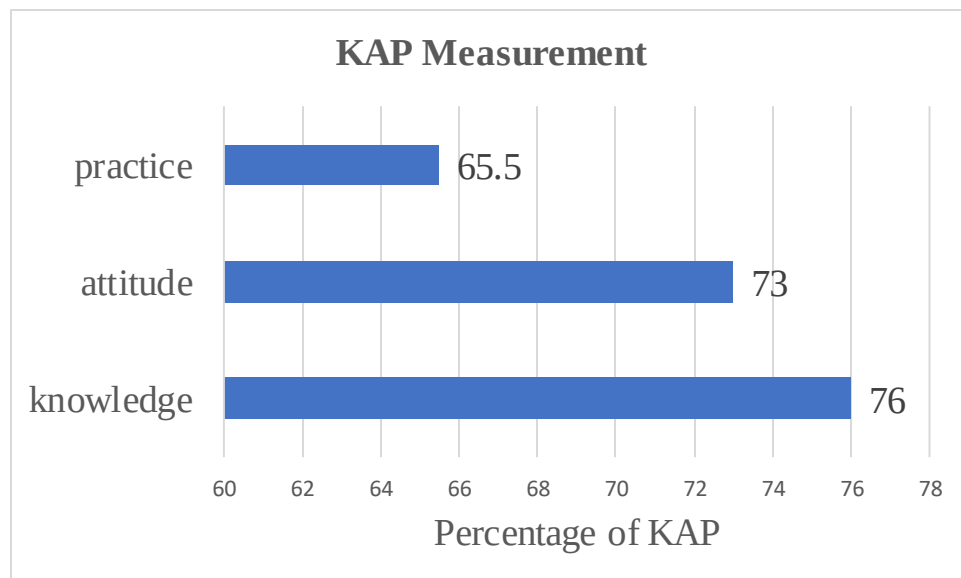


Figure 4.16: KAP Measurement

Analysis of the Knowledge, Attitude, and Practice (KAP) measurement in Figure 4.16 indicates that community perceptions toward MSWM are generally positive. The survey reveals high levels of knowledge (76%), attitude (73%), and practice (65.5%), suggesting a promising degree of engagement with environmental issues. Awareness of the environmental benefits of waste segregation reaches 96%, and 90% of respondents acknowledge its economic benefits. Furthermore, 77% support the enactment of legislation mandating waste segregation at the source.

Regarding behavioral intention, 80% of participants express willingness to cooperate with waste segregation efforts, and 95% support the placement of multiple containers for recyclable waste in residential areas. Awareness of the legal dimensions of waste management is also relatively high at 76%. However, overall satisfaction with the current performance of household waste management is notably low (49%), indicating a disconnect between community expectations and the existing waste management services.

This level of dissatisfaction may be attributed to insufficient communication with the public regarding ongoing procedures, challenges, and global waste management developments. Nevertheless, the high willingness to participate in improved waste segregation and recycling practices underscores the need for decision-makers to act decisively by introducing relevant legislation and practical measures to initiate systematic segregation programs (see Figure 4.16).

4.5 Tools, Administrative Alternatives, and Opportunities for Best MSWM Sustainability

Through interviews with 13 waste management experts, answers were obtained to the research questions regarding the management tools, alternatives, and opportunities that contribute to the sustainability of MSWM. The following is a summary and analysis of the experts' responses to the questions. Similar points are summed, and the overall percentages are given for each point.

4.5.1 Tools and Administrative Alternatives

In this section and the procedures that follow, the experts' answers to the questions asked them are arranged in the form of points, with the percentage for each answer mentioned.

4.5.1.1 Legislation, Policy, and Administrative Systems (LPAS)

A group of experts (1, 4, 5, 6, 7, 9, 10, 12, 13) addressed the importance of this category (measured by 69%). They suggest doing so by developing comprehensive laws and regulations with strict enforcement mechanisms, establishing effective governance structures, and appointing qualified decision-makers, citing examples such as banning single-use plastics, landfill fees, and national waste policies.

4.5.1.2 Community Awareness and Engagement (CAE)

A group of experts (1, 3, 4, 7, 9, 11, 13) addressed the importance of this category (measured by 54%). They suggest doing so through raising

awareness and involving the public in waste management, starting with school education, using media and campaigns to encourage waste sorting and environmental behavior, and emphasizing the role of citizens in reducing waste and sorting it at the source.

4.5.1.3 Infrastructure and Technological Innovations (ITI)

A group of experts (2, 3, 4, 8, 9, 10, 13) addressed the importance of this category (measured by 54%). They suggest doing so through investing in recycling infrastructure, waste-to-energy solutions, composting, using advanced tools such as GIS, LCA, and simulation for decision making, and creating well-designed waste containers, recycling plants, and facilities.

4.5.1.4 Economic Incentives and Investments (EII)

A group of experts (5, 7, 8, 10, 12) addressed the importance of this category (measured by 38%). They suggest doing so through encouraging private and public sector investments in waste management solutions, creating economic incentives such as subsidies for recycling or penalties for waste, and focusing on the financial sustainability of MSWM systems.

4.5.1.5 Sustainable Development and Research (SDR)

A group of experts (1, 10, 11, 12, 13) addressed the importance of this category (measured by 38%). They suggest doing so through aligning waste management policies with SDGs, balancing environmental, social, and economic needs, conducting research, collecting data to monitor trends and forecast future needs, and promoting the circular economy and reducing waste generation from the source. Figure 4.17 highlights the graphical representation of the expert consensus on key strategies for MSWM. Each bar represents the percentage of experts who emphasized a particular category.

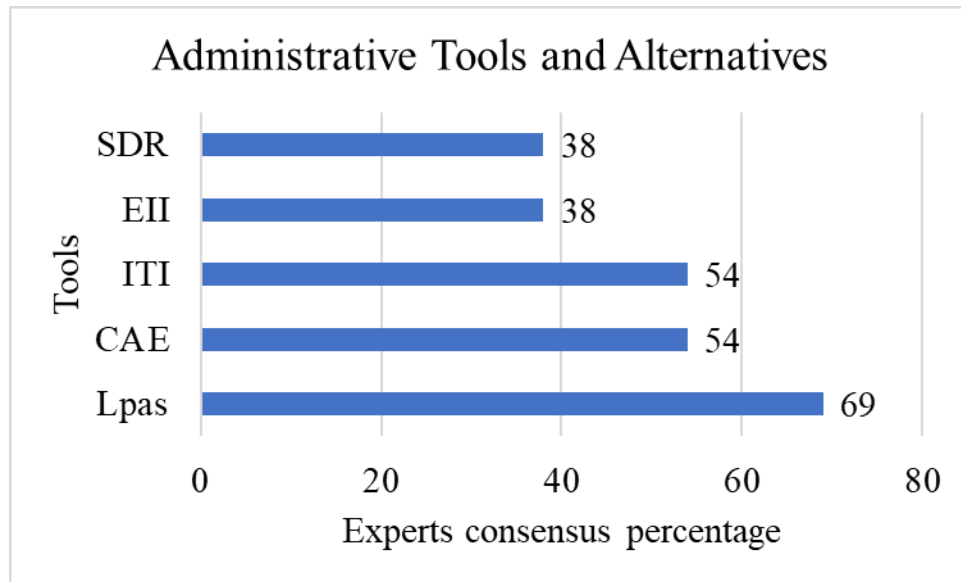


Figure 4.17: Expert consensus on key strategies for (MSWM)

(LPAS: Legislation, Policy, and Administrative Systems, CAE: Community Awareness and Engagement, ITI: Infrastructure and Technological Innovations, EII: Economic Incentives and Investments, SDR: Sustainable Development and Research)

4.5.2 Technology in Waste Management

To answer the question about incorporating technology into MSWM, 13 experts provided their insights. The common themes and percentages of agreement are summarized below, categorized into four main points.

4.5.2.1 Integration of Modern Technology in MSWM Processes (IMT)

Most experts (measured by 92%) stressed the importance of integrating modern technology into all aspects of waste management. They suggest doing so by including collection, sorting, treatment, and disposal. Technologies and

tools include AI-based sorting systems, smart bins and sensors, fleet and route optimization systems, and methane gas collection for energy use. Experts highlighted that such technologies enhance efficiency, reduce environmental impact, and optimize resources.

4.5.2.2 Data-Driven and Analytical Tools (DDAT)

Several experts (measured by 69%) have emphasized the need for data-driven approaches in waste management. They provide examples such as waste tracking software for trucks and containers, systems to analyze and visualize waste data for better decision-making, and predictive tools to estimate waste generation trends. This category highlights the role of digitization in delivering actionable insights to enhance MSWM outcomes.

4.5.2.3 Sustainable and Context-Specific Technological Applications (SCST)

Some experts (measured by 62%) stressed the importance of adopting sustainable and locally appropriate technologies. They cited several points, including designing systems to suit regional needs, such as smaller markets in the Gulf. Using energy-efficient technologies such as waste incineration with minimal environmental impact. Focusing on circular economy models through waste-to-energy and the reuse of materials.

4.5.2.4 Encouraging Public Participation via Technology (EPPT)

Several experts (measured by 54%) highlighted the role of technology in engaging the community. They are suggesting doing so through apps that reward users for sorting waste, platforms for citizen complaints, and feedback.

These approaches help raise awareness and encourage sustainable waste management practices among citizens. Figure 4.18 highlights the graphical representation of the expert consensus on technology in MSWM. Each bar represents the percentage of experts who emphasized a particular category.

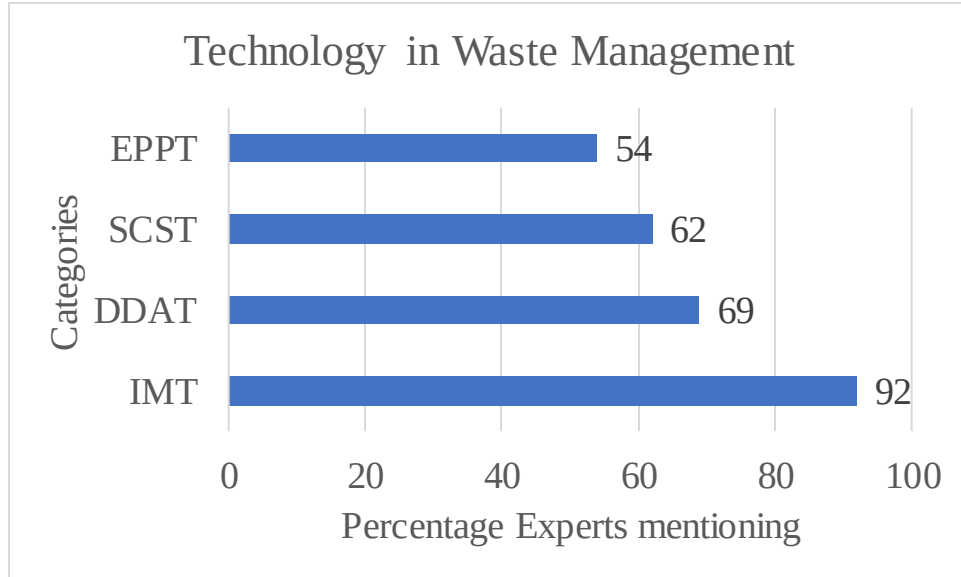


Figure 4.18: Expert consensus on Technology in MSWM.

(**IMT**: Integration of Modern Technology in MSWM Processes, **DDAT**: Data-Driven and Analytical Tools, **SCST**: Sustainable and Context-Specific Technological Applications, **EPP**: Encouraging Public Participation via Technology)

4.5.3 Use of AI in Waste Management

Summary and analysis of experts' opinions on the use of AI in waste management, categorized themes and percentages (Figure 4.19):

4.5.3.1 Improving Waste Sorting and Recycling

A group of experts (measured by 30%) suggested key points to improve waste sorting and recycling. They suggest using AI to improve sorting accuracy and enhance recycling operations. Smart waste bins and sensors automate waste sorting. Optical devices using AI achieve high efficiency and accuracy in sorting. They cited examples of AI-based systems in Abu Dhabi, Europe, and Korea.

4.5.3.2 Optimizing Waste Collection and Management

One-point experts (measured by 25%) have made to improve waste collection and management is that sensors in waste containers send signals when they are full. AI systems distribute crews and optimize collection routes. Comprehensive AI-powered programs can manage waste from collection to disposal.

4.5.3.3 Environmental and Sustainability Benefits

AI contributes to achieving the SDGs by reducing landfill waste. Early detection of sanitation violations supports environmental health. Predictive AI tools estimate waste volumes to minimize overproduction and manage resources. This point was measured by around 20% of experts.

4.5.3.4 Automation and Efficiency in Operations

AI facilitates faster and more accurate data processing and reporting. AI-powered chatbots streamline communications and interactions with customers. Automating repetitive tasks, such as site monitoring and report generation, saves time and effort. This point was measured by around 15% of experts.

4.5.3.5 Need for Research, Customization, and Awareness

Experts stress the importance of research in adapting AI to local needs. Successful implementation of AI requires understanding and training. Learning from global best practices (e.g., Europe and Asia) ensures better adoption. This point was measured by around 10% of experts.

Key Observations and Insights:

Experts stressed that the use of AI significantly improves the efficiency of waste management. It also achieves environmental benefits and achieves SDGs. The most prominent challenges include the lack of understanding of AI and the high costs of implementation. This can be addressed through local research and customization of the technology. Experts stress the need to adapt AI solutions to the specific context of Bahrain, taking into account the small market size and the unique requirements of the country.

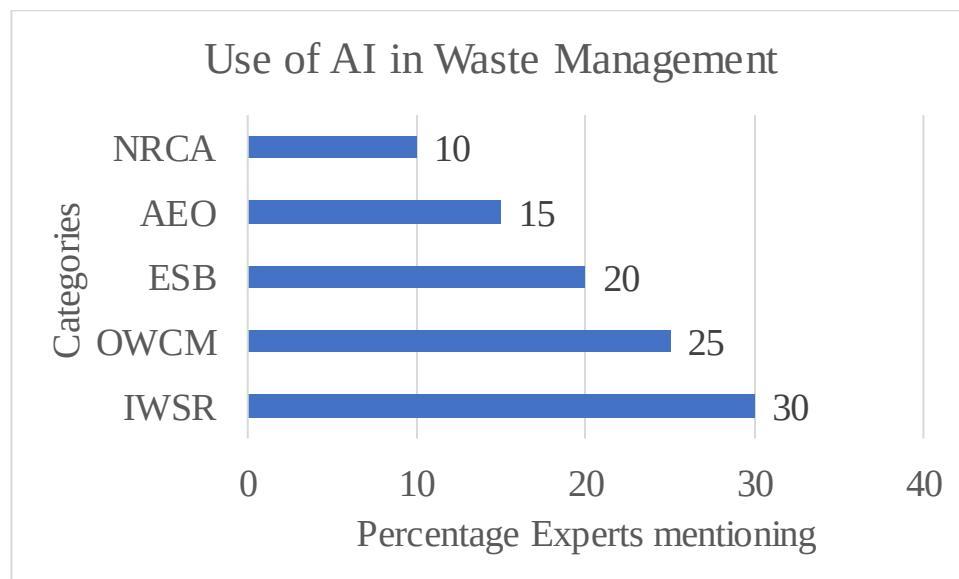


Figure 4.19: Expert consensus on use of AI in MSWM.

(IWSR: Improving Waste Sorting and Recycling, OWCM: Optimizing Waste Collection and Management, ESB: Environmental and Sustainability Benefits, AEO: Automation and Efficiency in Operations, NRCA: Need for Research, Customization, and Awareness)

4.5.4 Waste Sorting Methods in Bahrain

Summary and Analysis of Expert Opinions on Waste Sorting Methods in Bahrain. Categorized Themes and Percentages:

4.5.4.1 Two-Container System

Most experts, around 46%, advocate for starting with two containers, one for organic waste and the other for recyclables or general waste. Seen as practical, cost-effective, and aligned with Bahrain's current infrastructure and cultural readiness. Provides an entry point for transitioning to more advanced sorting systems in the future.

4.5.4.2 Multiple-Container System

Some experts, around 23%, support a system with multiple containers for different waste types (e.g., plastics, metals, organics). Viewed as ideal for achieving optimal waste segregation, but concerns include higher costs, infrastructure demands, and the community's readiness for such a system.

4.5.4.3 Legislation and Enforcement

Experts for around 15% emphasis on the importance of laws and regulations to mandate sorting and recycling. Examples include the successful implementation of plastic bag regulations and the need for legal frameworks to ensure compliance.

4.5.4.4 Community Awareness and Education

Experts for around 12% stress the need for public awareness campaigns to encourage waste sorting. Schools, religious institutions, and community initiatives are identified as key platforms for promoting a culture of sorting. Children are seen as effective agents of change within families.

4.5.4.5 One-Container System

A small minority, around 4%, believe that the current one-container system should remain due to a lack of infrastructure and challenges in citizen participation. Sorting could be managed downstream using centralized facilities. A broad consensus among experts suggests starting with two bins, making it easier for citizens to adopt waste sorting habits while addressing current infrastructure and logistical challenges. While a multi-bin system is the ideal solution, a phased approach starting with two bins is recommended. This is in line with Bahrain's infrastructure and allows for future expansion. Enforcing waste sorting through legislation was highlighted as crucial. Laws can drive behavioral change and ensure continuity in waste management practices. Education and awareness campaigns are essential to promote a sorting culture. Experts highlight the role of schools, religious institutions, and youth initiatives in driving this change.

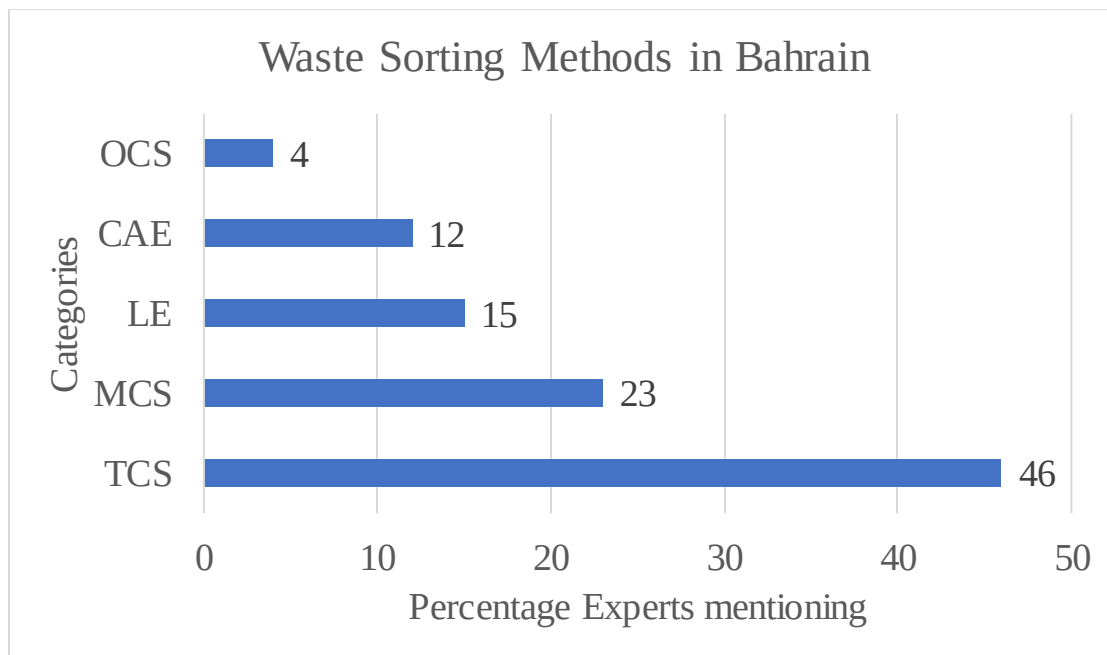


Figure 4.20: The expert consensus on waste sorting.

(TCS: Two-Container System, MCS: Multiple-Container System, LE: Legislation and Enforcement, CAE: Community Awareness and Education, OCS: One-Container System)

Figure 4.20 visually represents the expert consensus on waste management categorization. Each segment illustrates the percentage of emphasis given to each category.

4.5.5 Opportunities for Enhancing Waste Management

Many experts (36%) emphasize the potential of waste as an economic resource (WR), highlighting opportunities for energy generation, fertilizer production, recycling, and reusing materials. 22% also see the importance of engaging the community through awareness campaigns and educational initiatives, leveraging religious and cultural ties to drive participation in waste

management practices, and using educational institutions, mosques, and funeral homes as key platforms for community mobilization (CEA).

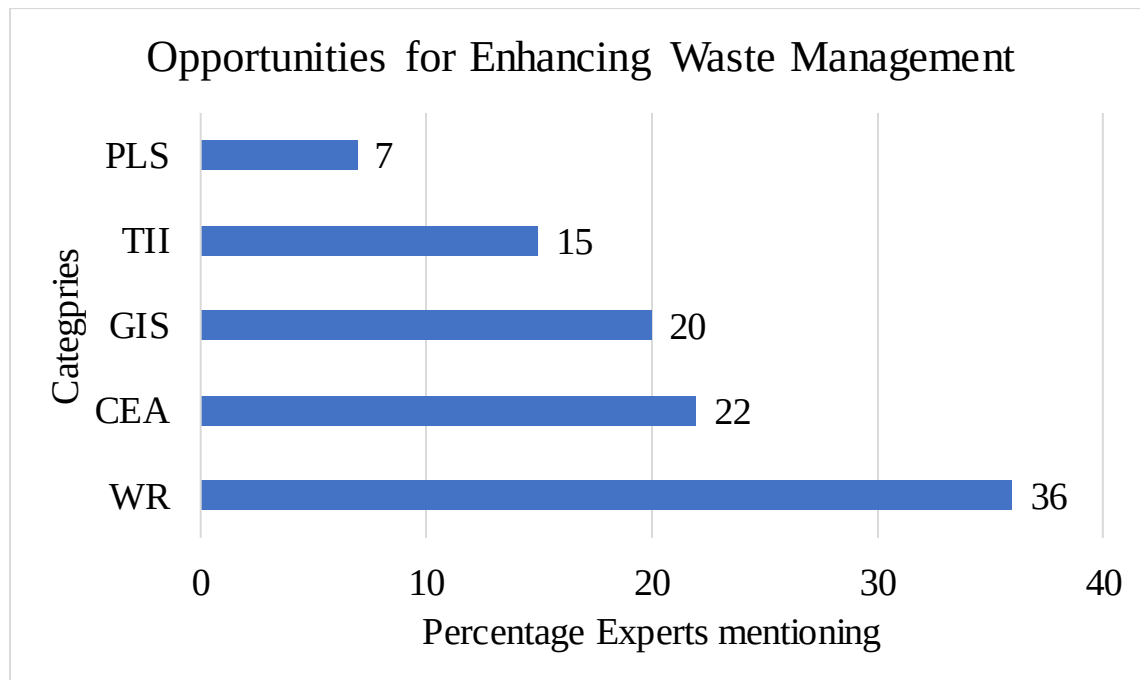


Figure 4.21: The expert consensus on opportunities for enhancing waste management.

(PLS: Policies and Legislation for Sustainability, TII: Technological and Industrial Investment, GIS: Government, Industry, and Stakeholders, CEA: Community Effectiveness Analysis, WR: Waste Recycling)

20% of experts emphasize the importance of government support by developing stronger strategies, enforcing laws, and strengthening partnerships (GIS). 15% see the importance of technological and industrial investment and technological innovations (TII). 7% also see the importance of policies and legislation for sustainability (PLS), by stimulating private sector participation and setting annual waste reduction targets. Figure 4.21 represents all those percentages.

Experts see several key points for sustainable waste management. They see waste as a financial opportunity and resource generator. To achieve sustainability in waste management, community engagement and awareness must be built through educational campaigns and community-led initiatives. Collaboration among multiple stakeholders is essential for long-term success. Technology and innovation are opportunities to improve efficiency and reduce environmental impacts. Incentive policies further enhance waste management outcomes.

4.5.6 Bahrain's Readiness for Waste Treatment

Experts for around 40% of Bahrain is not yet ready to comprehensively manage waste due to a lack of infrastructure, facilities, and government-led initiatives. (30%) of experts believe that the private sector has a role to play in waste management efforts by enhancing cooperation, providing incentives, and easing restrictions. (15%) of them believe that political will, strategic planning, and supportive legislation are crucial to enhancing waste management in Bahrain. Some experts (10%) advocate converting waste to energy, which would significantly reduce reliance on landfills. (5%) of them suggest that cooperation with international stakeholders and adopting global best practices are interim solutions. Figure 4.22 illustrates the distribution of expert consensus on waste management themes.

Experts have provided their views on Bahrain's readiness to develop waste management, and here is a summary. Infrastructure development is crucial, with the provision of local recycling plants and processing facilities. Private sector engagement is key to recycling, and further incentivizing its participation can help bridge the readiness gap. The government should adopt

clear waste management strategies, supported by legislation and feasibility studies, to lay the foundation for sustainable waste management.

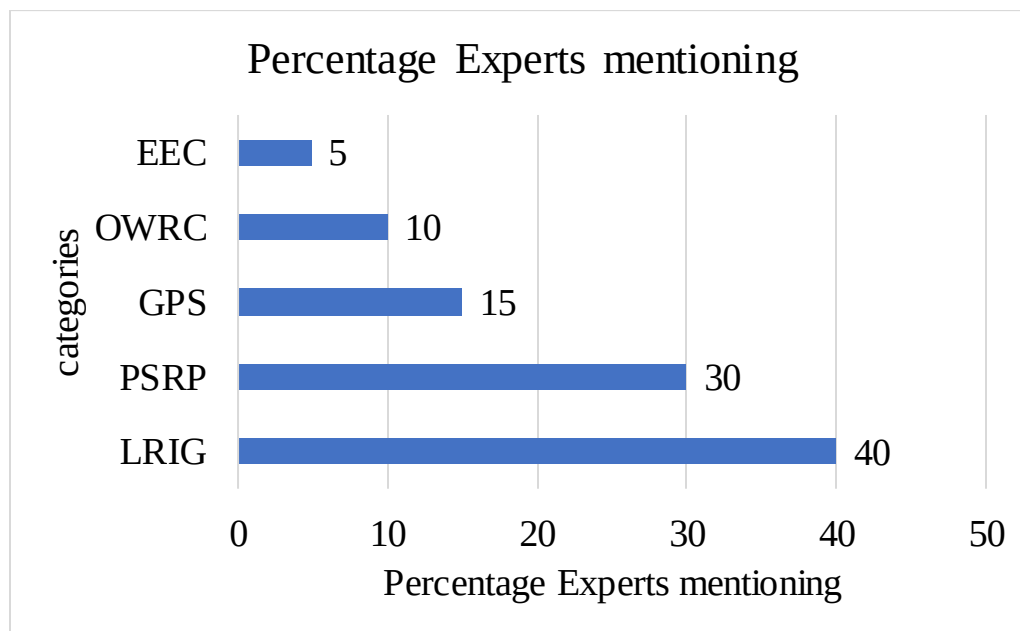


Figure 4.22: Percentage of experts' opinions on Bahrain's Readiness for Waste Treatment

(EEC: Environmental and Energy Conversion, OWRC: Organizational and Waste Recycling Capacity, GPCS: Government Policies and Strategic Capacity, PSRP: Private Sector Role and Participation, LRIG: Local Readiness and International Gap)

The government should embrace advanced technologies such as waste-to-energy and waste-derived fuel, which can improve waste utilization and reduce reliance on landfills. Until local capacity is developed, waste exports and collaboration with international partners are essential measures to bridge the gap.

4.5.7 Transforming for waste-to-energy in Bahrain.

(35%) of experts stress the need for waste-to-energy due to limited landfill space in Bahrain. (25%) of experts cite high economic costs and the need for feasibility studies as recurring concerns, making waste-to-energy less cost-effective. (20%) of them find concerns about potential environmental pollution from emissions, public resistance due to health risks, and proximity to residential areas to landfills to be important considerations. (15%) of experts suggest learning from global experiences, citing international best practices in waste-to-energy projects. (5%) of experts believe that legislative support, government support, and clear regulations are essential for the success of waste-to-energy projects. Figure 4.23 visualizes the expert consensus on WTE management.

Experts suggest conducting feasibility studies for waste-to-energy projects tailored to Bahrain's specific needs. Priority should be given to environmental safeguards, and public participation should be ensured to address health concerns. Encourage private sector participation in waste-to-energy with financial and regulatory support. Learn from regional and global successes and collaborate with experienced countries to gain insight into effective waste-to-energy implementation. Develop a regulatory framework by introducing laws that enforce waste-to-energy practices while ensuring environmental and economic feasibility.

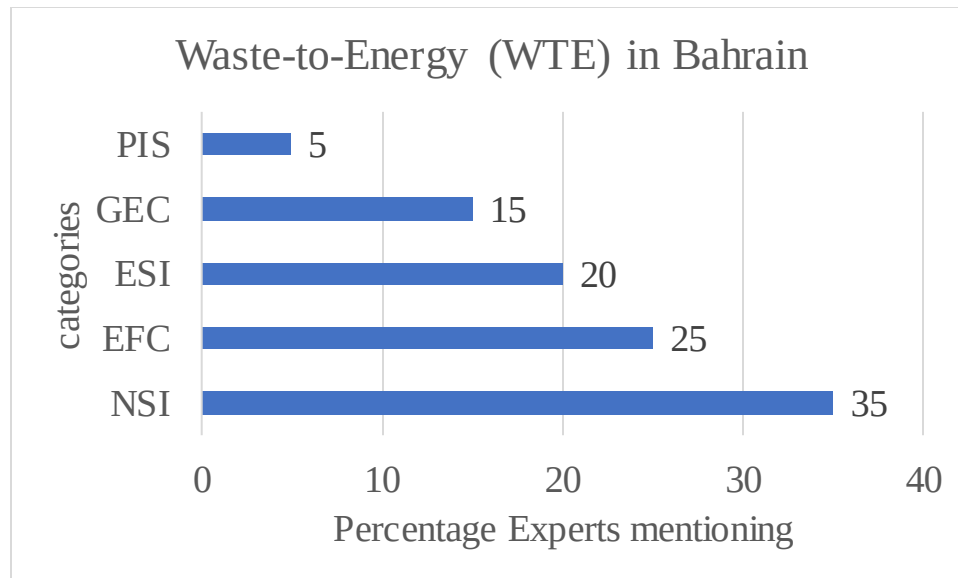


Figure 4.23: Percentage of experts' opinions on WTE in Bahrain.

(PIS: Public and Institutional Support, GEC: Global Experience and Collaboration, ESI: Environmental and Social Impact, EFC: Economic and Financial Concerns, NSI: Need for Spatial and Infrastructure Solutions)

4.5.8 Cost-Effectiveness and Appropriate MSWM Methods in Bahrain.

Experts discussed various topics related to cost-effectiveness and appropriate waste management methods in Bahrain, as shown in Figure 4.24. Most experts felt that sorting and recycling (40%) are the most practical and economically viable solutions for Bahrain, considering the waste composition and limited land resources. They also believe that economic feasibility is of paramount importance (30%) for decision-making but must be combined with environmental and social considerations. They recommended that costs should be balanced with long-term benefits. Experts believe that waste management should be integrated (15%), so that, in addition to sorting and

recycling, other methods such as composting organic waste and converting waste to energy should be considered. Experts believe that public awareness and education are essential for successful waste management (10%). Educating citizens promotes better sorting at source and reduces overall waste management costs. Targeted campaigns can increase public participation in recycling and composting efforts. Experts believe that it is important to prioritize health and environmental impacts (5%) over immediate economic gains.

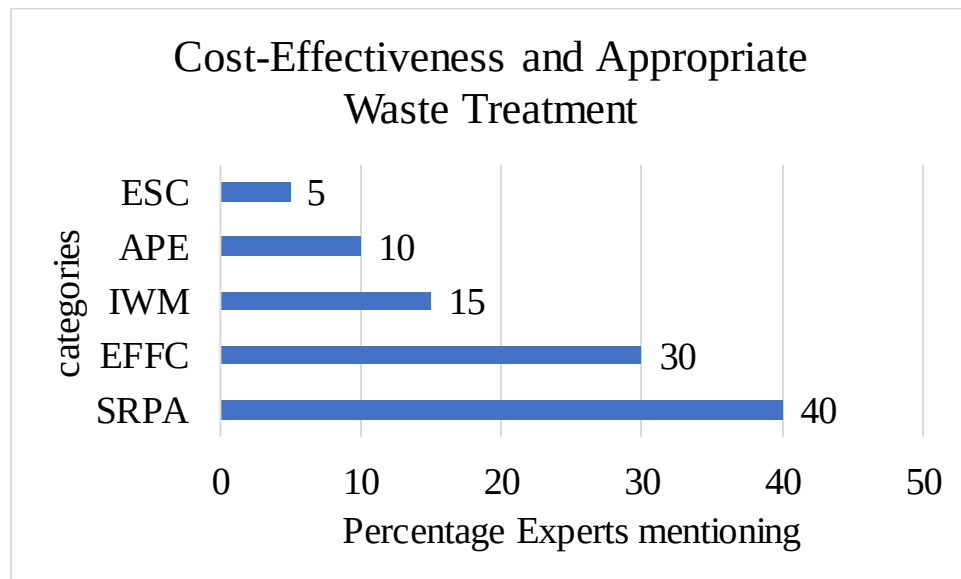


Figure 4.24: Percentage of experts' opinions on cost effectiveness and appropriate waste management.

(ESC: Environmental and Social Considerations, APE: Awareness and Public Education, IWM: Integrated Waste Management, EFFC: Economic Feasibility and Financial Considerations, SRPA: Sorting and Recycling as Primary Approach)

4.5.9 Summary of experts' interview

The integration of advanced technology, policy frameworks, and public engagement is vital for sustainable waste management. Bahrain requires a gradual approach focusing on sorting, recycling, and WtE technologies, supported by policy and economic incentives.

4.6 Impact on Achieving SDGs

The answers and the points addressed by the experts are in line with the SDGs, particularly in the areas of waste reduction (Goal 12), environmental protection (Goal 13), and sustainable communities (Goal 11). Effective waste management contributes to resource efficiency, climate resilience, and the circular economy, driving progress across multiple SDGs.

4.6.1 Ranking of Scenarios of Waste Management Based on Expert Answers

The result of ranking the scenarios based on experts' answers is shown in Table 4.17.

Table 4.17: Ranking MSWM scenarios based on experts' answers.

Ranking Scenario	Reasons	Experts
Recycling	* Most practical and cost-effective, reducing landfill, maximizing resource recovery. * Strong alignment with environmental and sustainability goals.	1, 2, 3, 4, 5, 7, 9, 10, 11, 12, 13.

Composting	* Effective for managing organic waste, reducing methane emissions from landfills, and producing valuable fertilizers. * Suitable for Bahrain's waste composition.	1, 3, 4, 7, 9, 10.
Anaerobic Digestion	* Offering both environmental and energy benefits. * Less emphasized compared to composting due to higher implementation complexity.	2, 4, 5, 9, 12.
Gasification	* Reduces landfill dependency and generates energy. * Seen as promising but requires significant investment and feasibility studies.	3, 5, 8, 10, 13.
Incineration	* Provides immediate landfill relief and energy recovery. * Concerns over high costs, emissions, and public acceptance.	1, 4, 7, 11, 13.
Sanitary Landfill	* Considered a necessary interim solution while more sustainable methods are developed. * Minimizes environmental risks compared to open dumping.	2, 6, 9, 10, 12.
Landfill (Traditional)	* Viewed as the least desirable option due to environmental and health risks. * Only considered when other solutions are unavailable.	6, 8, 10.

The results of this study, which was conducted through interviewing experts in waste management and sustainability, are consistent with previous research. Abas et al. (2022) found that policymakers do not allocate sufficient resources to waste management. This study identifies the need for advanced technology in Bahrain. Experts considered the best scenario for Bahrain, depending on the circumstances and conditions, to be a waste recycling approach. Bahrain's steps to invest in agricultural waste composting are steps that must be continued and strengthened to conserve resources, reduce harmful environmental impacts, and generate revenues. Experts believed that the proper implementation of advanced technologies in the MSW sector can play an important role in ensuring a pollution-free environment in the long term. In addition, most respondents focused on the social awareness factor as a fundamental pillar for the success of the waste recycling approach.

4.6.2 Exploring the best Technologies and electronic systems for sustainable MSWM

In Bahrain, the main barrier to technology adoption is the lack of adequate availability and, according to experts, the lack of awareness to maintain it. Most respondents expect that technology will cost a lot to maintain if used without prior awareness. It can be used in places where it can be monitored and controlled (high-income places or places where there are cameras).

The proposed technology, as extracted from the literature review in chapter 2 and as taken from the experts' interviews, included a variety of innovative tools and techniques to improve waste management. These include AI technologies, which monitor violations and prepare detailed reports, waste sorting using AI-based systems, waste tracking and reducing inefficiency, and

applications for composting programs using AI. Smart containers and sensors can be used, waste levels in containers can be monitored, and smart sorting systems based on sensors can be used to improve efficiency. Through technology, tracking and optimization systems can be used, using RFID technology, and optimizing waste collection truck routes. There are advanced sorting technologies, and optical devices based on AI can be used to sort waste with greater accuracy. Sustainable technologies and advanced processing can be used to capture methane gas from landfills, and advanced electronic management systems can be used to process waste. Mobile applications can be used to motivate individuals to sort waste through reward systems using applications and digital incentives. The experts also emphasized the focus on customized solutions that suit the local environment of Bahrain, such as adopting global technology with the necessary modifications. In this conclusion, the fourth objective of the research objectives is achieved.

4.7 LCC Results

After running LCC in OpenLCA, the results were as shown in Table 4.18.

Table 4.18: The results of LCC for all scenarios using OpenLCA.

Scenario	LCC Result (Added value) US\$/kg
Gasification	-0.541670396
Composting	-0.489338039
Recycling	-0.310547047
Sanitary Landfill	-0.279699541

AD	-0.226670396
Incineration	-0.201074541
Landfill	-0.196020396

In Table 4.18, the product LCC outcomes for all scenarios are ranked in order of best outcome using the value-added option. This ranking reflects the best value-added options, with gasification performing best (highest negative) (-0.542) and landfill performing worst (-0.196). Negative product LCC outcomes in waste management have a different meaning. Waste treatment may be able to generate revenue (energy production, composting, and material recycling). This can lead to significant savings (reduced landfill costs, lower environmental impact fees). The initial investment may seem like a loss, but in the long run, it has a positive impact. In this case, the more negative the number, the better the financial outcome. In this study, the gasification scenario appears to be the most attractive option, with the highest negative value. This suggests that it may generate the most revenue or savings relative to its costs. Composting and recycling come in close second, suggesting that they also provide significant financial benefits. Landfill options (sanitary and conventional) show lower negative values, indicating that they may be less financially beneficial in the long run. Anaerobic digestion and incineration fall in the middle, offering moderate financial benefits.

For waste management decisions, these negative waste LCC outcomes are promising, and it is important to note that financial considerations are only one part of the decision. Decision makers must consider multiple factors, including environmental impact, local regulations and policies, community

acceptance, and technological feasibility. Analysis of the waste LCC outcomes showed that gasification, composting, and recycling appear to be the most attractive options in this scenario.

4.8 The best scenario for the treatment of MSW in Bahrain

In this section, all scenarios were compared from the economic, environmental, and social aspects and evaluated to choose the most appropriate one for implementation that suits Bahrain's environment and situation Table 4.19.

Table 4.19: Comparison of scenarios based on Environment, Economics, and Social.

Rank	Economic criteria (LCC)	Environmental criteria (LCA)	Social criteria
1	Gasification	Incineration	Recycling
2	Composting	SL	Composting
3	Recycling	Composting	AD
4	SL	Recycling	Gasification
5	AD	AD	Incineration
6	Incineration	Gasification	SL
7	Landfill	Landfill	Landfill

Table 4.19 shows the results of the trade-offs made in the previous sections of this chapter, which were between economic, environmental, and social criteria. It is clear from the sum of these trade-offs that the treatment methods are different. Therefore, the comparison requires a scientific evaluation of the trade-offs between these methods and opinions according to the proposed criteria.

To rank the scenarios according to the best for MSWM in Bahrain, the ranked results for each pillar (Economic, Environment, and Society) can be combined using an MADM methodology. The steps can be simplified as follows:

1. Assigning weights to each pillar: You need to determine the relative importance of each pillar (economy, environment, and society) based on national priorities or overall objectives (the methodology for determining weights depends on the specific environmental, economic, and social objectives of the Kingdom of Bahrain).
2. Calculating points for each scenario is allocated based on the ranking of each scenario in each pillar (the best scenario gets the highest points).
3. Merging points based on weights, the aggregate points for each scenario are calculated by adding the weighted points for each pillar.

Practical steps for ranking scenarios:

1. Assigning points to each ranking:
First place = 7 points, second = 6 points, and so on until the last = 1 point.
2. Initial score as in Table 4.20 for each scenario.

Table 4.20: Scoring the scenarios of MSWM.

Scenario	Economic	Environment	Society
Gasification	7	2	4
Composting	6	5	6
Recycling	5	4	7
Sanitary landfill	4	6	2
Anaerobic Digestion (AD)	3	3	5
Incineration	2	7	3
Landfill	1	1	1

3. Calculating the aggregate points for each scenario

To calculate the total points for each scenario, the points of each pillar are multiplied by its weight (here will assume =33.3% for each scenario), and then the results are added.

Equation: Total points = (Economy x 0.333) + (Environment x 0.333) + (Society x 0.333)

The accounts:

Gasification: $(7 \times 0.333) + (2 \times 0.333) + (4 \times 0.333) = 4.329$

Composting: $(6 \times 0.333) + (5 \times 0.333) + (6 \times 0.333) = 5.661$

Recycling: $(5 \times 0.333) + (4 \times 0.333) + (7 \times 0.333) = 5.328$

Sanitary landfill: $(4 \times 0.333) + (6 \times 0.333) + (2 \times 0.333) = 3.996$

Anaerobic Digestion (AD): $(3 \times 0.333) + (3 \times 0.333) + (5 \times 0.333) = 3.663$

Incineration: $(2 \times 0.333) + (7 \times 0.333) + (3 \times 0.333) = 3.996$

Landfill: $(1 \times 0.333) + (1 \times 0.333) + (1 \times 0.333) = 0.999$

4. Final Ranking. The ranking from highest to lowest is:

According to Figure 4.24, the highest score for different waste management technologies was for the composting method (5.661), followed by the recycling method (5.328), and in third place was the gasification method (4.329).

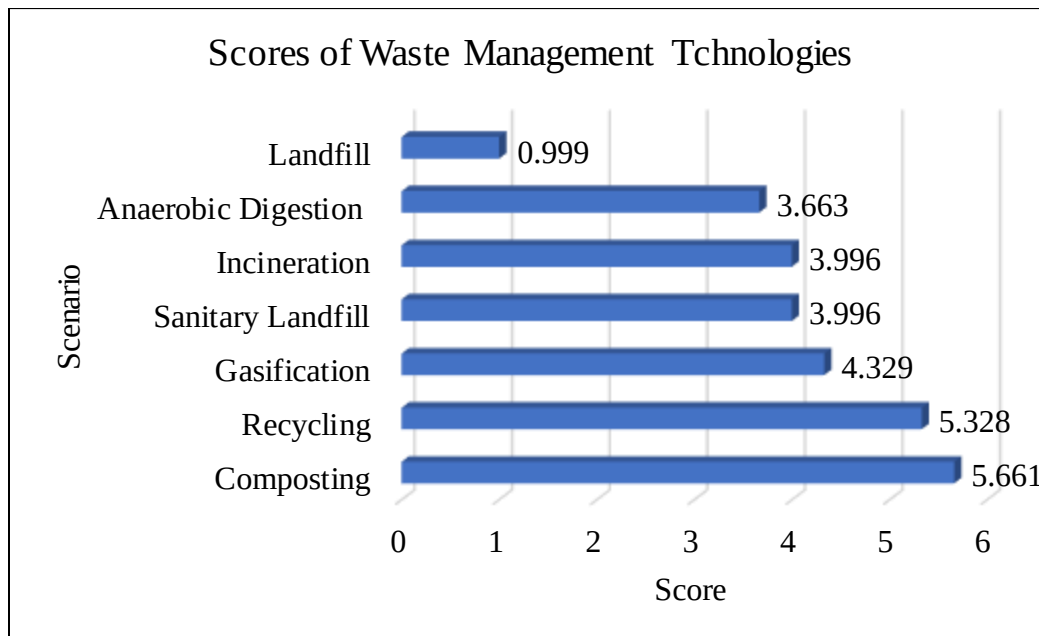


Figure 4.25: The scores for different waste management technologies.

4.9 Evaluating Sustainable MSW Treatment Options

This thesis evaluates MSW treatment methods in Bahrain, both recent and proposed, based on sustainability criteria encompassing economic, environmental, and social pillars. Utilizing a weighted scoring approach, the study ranks seven treatment methods to determine their suitability, as shown

in Figure 4.25. Composting (5.661) emerges as the most sustainable option, followed by recycling (5.328) and gasification (4.329). Sanitary landfill and incineration tie (3.996), with anaerobic digestion (3.663) slightly trailing. Landfill ranks lowest (0.999) due to its limited sustainability benefits. The findings aim to guide policymakers in implementing effective, sustainable MSW management strategies tailored to Bahrain's unique socio-economic and environmental context.

This study shows that landfills are the worst-case scenario for human and environmental harm. Cost analysis results, along with similar classifications of studies, indicate that landfills alone or in combination with recycling and/or biological treatment methods are preferable. Waste management operations worldwide employ a variety of treatment technologies. These range from basic methods, such as open dumping/incineration, to advanced treatment methods, such as engineered landfills and various thermal and biological treatment methods with resource recovery systems, from source segregation to recycling, treatment, and final disposal. Numerous studies have shown that composting has the lowest environmental impact, in addition to its economic benefits and contribution to improved performance (Vargas, Q. R., 2014; Levis et al., 2014; Yay, A. S. E., 2015; Alias et al., 2016; De Feo et al., 2016; Bantias et al., 2020; Erhun, M., 2022).

4.10 Assessment of achieving SDGs related to MSWM.

Table 4.21 summarizes Bahrain's progress in achieving SDGs related to MSWM, based on VNR1 and VNR2 reports. It highlights achievements in waste collection, recycling initiatives, emissions reduction potential, and international partnerships. However, challenges persist, including low public

awareness, infrastructure gaps, and high reliance on landfilling. Scores range from 3 to 4, reflecting moderate to strong alignment with SDG targets.

Table 4.21: Assessment of Achieving SDGs related to MSWM.

SDGs	Achievements	Challenges	Score
SDG 11: Sustainable Cities and Communities	100% of MSW is collected and managed in controlled facilities as of 2020	Pressure from population growth and insufficient infrastructure for municipal waste sorting.	4
SDG 12: Responsible Consumption and Production	1.38 million tons of MSW were generated in 2020. 98% landfilled; 1.7% recycled; 0.05% composted. Recycling rate of construction/demolition waste: 379,000 tons in 2019–2020. Green waste recycling: approximately 3,000 tons from 2018 to 2020. Recycled from households (2018–2020): 246 tons total;	Low public awareness and a lack of widespread sorting at the source.	4

	66% paper, 32% plastic, 1.5% metal.		
SDG 13: Climate Action	MSW generates 6.2% of Bahrain's total GHG emissions. Projected methane (CH ₄) emissions from landfills in 2030: 22–63 Gg. Estimated landfill gas-to-energy potential: 57.4 GWh/year, powering 488 households (2020–2035).	High carbon emissions due to continued reliance on landfilling.	3.5
SDG 3: Good Health and Well-being	380 t/day industrial waste, 7 t/day hazardous and medical waste data.	High per capita waste generation is impacting public health indirectly.	3.5
SDG 8: Decent Work and Economic Growth	Carbon capture plant capturing 450 t/day CO ₂ from flue gases (Circular economy investments).	Limited investment in green job sectors for waste management.	3.5
SDG 9:	92% of MSW goes to controlled landfills; 8%	Limited industrial-scale waste recycling facilities.	3.5

Industry, Innovation, and Infrastructure	recycled as of recent data. Domestic adoption of GPS, RFID, bin app, and digitizing collection.		
SDG 14: Life Below Water	Legislation to reduce marine pollution, beach cleanup campaigns.	Ongoing marine waste issues are affecting seawater quality.	3
SDG 15: Life on Land	Askar landfill exceeds 700 acres, nearing capacity. Construction/demolition recycling: 379,000 t in 2019–20 helps reduce land pressure. Biosafety action plans, regulations protecting biodiversity from waste impacts.	Limited coverage for biosafety and biodiversity safeguards.	3.5
SDG 17: Partnerships for the Goals	Global methane treaty signatory, Estidama Center, UN technical support.	Insufficient leveraging of global best practices in waste infrastructure.	4

	Foreign PPPs: e.g., China's CNTY bid for WtE incinerator (~390,000 t/year capacity)		
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4.11 Validate the model and compare it with the models and cases.

The proposed SELECT model (social, environmental, legislative, energy, cost-effectiveness, and technical) is an innovative model for assessing sustainability in MSWM. It combines six key dimensions that influence the effectiveness and sustainability of a system. To verify its validity and reliability, it was compared to international models used in this field, such as the Integrated Sustainable Waste Management (ISWM) model, which includes social, institutional, environmental, and economic dimensions, but without a clear separation of energy and legislative variables as independent factors (van de Klundert & Anschütz, 2001). Furthermore, a comparison with the Sustainability Assessment of Technologies (SAT) framework, which assesses environmental, social, technical, and economic aspects, showed that the SELECT model outperforms by adding the legislative and energy dimensions, enhancing its accuracy in developing countries or countries undergoing legislative transitions. Furthermore, a review of stakeholder feedback in the Kingdom of Bahrain—through surveys, questionnaires, and government documents—contributed to verifying the model's realism and suitability for the local context, particularly in light of the challenges related

to environmental laws and energy generated from waste. This comparison supported the validity of the model by demonstrating broader areas of integration, not limited to traditional aspects. It also aligns with research recommendations calling for a comprehensive approach to assessing the sustainability of waste management systems in developing countries, such as Ferronato & Torretta (2019), who called for enhancing the application of LCA within more comprehensive frameworks.

4.12 Summary of Chapter 4

This chapter presented the empirical findings, directly addressing each objective. It evaluated the environmental impact of the current MSWM system through LCA, identifying composting and recycling as the most sustainable options, achieving the first objective. It assessed Bahrain's progress towards the relevant SDGs, revealing strengths in SDGs 11 and 12 but moderate performance in SDG 13, achieving the second objective. It then examined management tools, alternatives, and stakeholder views to assess policy effectiveness and opportunities, achieving the third objective. Scenario analysis using LCA and LCC contributed to the selection of optimal technologies, directly addressing the fourth objective and validating the SELECT framework.

Chapter 5: Discussion and Conclusions

5. Introduction

This chapter presents an in-depth assessment of the current performance of MSWM in Bahrain concerning sustainability objectives. It addresses the study's first objective through data analysis, expert insights, and LCA. The chapter also evaluates the extent of SDG achievement, explores appropriate administrative and technological tools, and identifies the optimal waste treatment scenario. It highlights opportunities for improvement based on national reports and international studies. The findings serve as a foundation for linking policy, practice, and sustainability in MSWM.

5.1 The current performance of MSWM (Objective1)

1. With the planned policy of the Government of the Kingdom of Bahrain to develop MSWM into an advanced approach, advanced steps and appreciated attempts have been implemented related to investing agricultural waste in composting and investing demolition and construction waste, which leads to exploiting land areas and preserving the natural resources of the earth and for future generations.
2. The assessment of MSWM was based on available data on the quantity and composition of solid waste from the Bahrain Data Platform, the opinions of experts in the field of waste management on the status of MSWM and sustainability in Bahrain, and a literature review. The environmental impact of the currently used waste treatment scenario was also evaluated by the LCA method using OpenLCA and compared with several options. The LCA method can assess the environmental impact as found from the results, but it is unable to address noise, odor, and working conditions. Therefore, users

of LCA should consider the model as a decision support tool and not a decision-making tool (Kirkeby et al., 2006).

3. The currently used method, which is landfill, is the worst and is not recommended to continue because it affects the environment and humans and depletes resources. The researcher recommends starting with waste segregation as a starting point for sustainable MSWM in the Kingdom of Bahrain, due to the scarcity of space in the Kingdom of Bahrain and the need to think about preserving people and the environment for a sustainable environment.
4. The Ministry of Municipal Affairs is responsible for collecting and transporting bulky waste and is responsible for providing families with correct information about household waste management and is responsible for developing and sustaining waste management by taking serious steps.
5. This study benefits from the need to monitor household waste management and develop waste management indicators related to the quantities, types, and percentages of recyclable materials that provide information about the actual environmental impact.

5.2 The extent to which SDGs have been achieved (Objective 2)

From the above, it is concluded that SDGs 11, 12, and 17 show significant progress in strategic policies, partnerships, and urban sustainability initiatives. SDGs 14 and 13 require further improvement and focus, especially in mitigating the impact of waste on marine environments and reducing reliance on landfills. Bahrain shows relatively consistent efforts in both direct and indirect targets, reflecting its alignment with the SDGs (balanced

development). This assessment highlights Bahrain's achievements while identifying areas where additional efforts are required to align with global and regional SDGs commitments.

5.3 Appropriate Tools, Administrative Alternatives, and Opportunities for Sustainable MSWM (Objective 3)

1. Issues and solutions for MSWM depend on the prevailing socio-economic conditions and not just on the volume of waste. Lack of attention to waste segregation and recycling hinders optimal waste management. Factors leading to optimal waste management include creating a positive environment for public-private partnership and all stakeholders, organizing and defining responsibilities for each category, and encouraging them to take initiative in projects (Hettiarachchi et al., 2018).
2. Tools and administrative alternatives that the research has reached are developing legislation, policies, and administrative systems with strict enforcement mechanisms, establishing effective governance structures, and appointing qualified decision-makers.
3. Raising awareness and engaging the public in waste management, starting with school education, using media and campaigns to encourage waste sorting and environmental behavior, and emphasizing the role of citizens in reducing and sorting waste at the source.
4. The importance of investing in recycling infrastructure, waste-to-energy solutions, composting, using advanced tools such as geographic information systems, LCA, and simulation for decision-making, establishing well-designed waste containers, recycling plants, and facilities.

5. The importance of encouraging private and public sector investments in waste management solutions, creating economic incentives such as recycling subsidies or waste penalties, and focusing on the financial sustainability of MSWM systems.
6. To determine the best policy for sustainable MSWM, waste management policies must be aligned with SDGs, balancing environmental, social, and economic needs, conducting research and collecting data to monitor trends and predict future needs, promoting the circular economy, and reducing waste generation at the source.

5.4 Appropriate Technologies for Sustainable MSWM

Smart methods can be used to manage waste and reduce its quantity. The latest Internet of Things (IOT) systems can be activated to organize household waste management based on machine learning to make waste management more efficient. Technology can be used to sort waste at the individual and community levels, as control devices can be linked and connected via the network and linked to a database that operates automatically without human-computer interaction. Based on these systems, one of the SDGs, which is smart cities, can be achieved (Dubey et al., 2020).

5.5 Best Scenario for Treating MSWM

The results showed that the best method for waste treatment in Bahrain is composting, followed by recycling, then gasification. This is supported by Vargas, Q. R. (2014), who found that fertilization with homemade fertilizers had the best environmental performance. The results of Ouedraogo et al. (2021) indicated that gasification has a lower impact on

human health compared to landfilling, and the organic compounds and metals produced during landfilling of MSW are more toxic than gasification. The results of the study by Dastjerdi et al. (2021) showed that the treatment of combustible waste through gasification and plastic recycling has the lowest environmental burdens in the GWP phenomenon. Home composting has many benefits and helps in achieving economic savings instead of purchasing fertilizers. It is a sustainable method of treating household waste and is compatible with the axes of sustainable development (economic, social, and environmental). The use of organic materials from MSW can be used as a sustainable alternative to fertilizers. The analysis of the studies also revealed that the integration of recycling, treatment and disposal technologies is the most appropriate strategy, and that the choice of these technologies, their implementation and their performance depend on the technological, social, and economic background of the region (Iqbal et al., 2020).

- Although each method has its costs and drawbacks, waste separation should be initiated and advocated to save the situation of increasing waste accumulation and its negative impact on the environment. Martínez-Sánchez et al. (2015) found that source separation resulted in higher financial costs than the alternative of burning organic waste with residual waste, which amounted to 1.6 million euros/year, the costs of additional bins and bags used by households, as well as additional collection operations.
- This study suggests that an environmental impact assessment of the waste management system should be carried out for each waste system and that the system should be improved by developing recycling through waste separation. The study emphasizes the importance of establishing and

promoting waste segregation at the source in society, the need-to-know data and information about waste, and the need to assess the current waste situation, as confirmed by Bernstad, A. (2010). The study was conducted to evaluate the environmental impacts of current waste management, recycling behavior, and choices among alternatives for different waste treatment methods using the LCA tool. The study concluded that supporting and improving waste sorting strategies leads to reducing environmental impacts. Zhou et al. (2022) found that the sustainability rating of SWM in China increased when the recycling rate increased.

- The study emphasizes the need to enact laws and regulations for household waste separation in the Kingdom of Bahrain, as confirmed by Kirkeby et al. (2006).

5.6 Opportunities to Improve Effects of MSWM

To reduce metal leaching and its effects, solid waste can be used in road construction through asphalt mixture, road backfill, and concrete aggregate (Ouedraogo et al., 2021). The impacts caused by the landfill of MSW are related to the release of gases into the atmosphere, metals, odor, NH₃, and NH₄. These gases cause GWP, environmental toxicity, acidification, and smog formation potential, which in turn leads to the depletion of the ozone layer and consequently the increase in respiratory diseases. Here comes the role of proper management of the gas produced using efficient collection and conversion systems, such as converting it to heat and electricity or gas flaring, which would mitigate the environmental and human health impacts (Ouedraogo et al., 2021). Leachate poses a risk to groundwater, soil, aquatic life, crops, and animals. Human health is indirectly affected when people

consume goods contaminated with the substance. Landfills are a starting point for groundwater contamination (Ouedraogo et al., 2021).

This is a summary of the opportunities for MSWM extracted from VNR1 and VNR2 of Bahrain (Bahrain.bh, 2025).

- The Constitution of Bahrain has contributed to establishing the necessary foundations for community work in line with the SDGs.
- The government's strategic plan has contributed to improving waste management.
- The Economic Vision 2030 emphasized the transition to a sustainable, productive economy by utilizing waste, recycling it, and preserving resources.
- Bahrain included 78% of the SDGs in VNR1 in 2018 and is working to improve waste management.
- High economic growth—37.4% in 2018 and 4.9% in 2023—has encouraged investment and contributed to improvements in waste management.
- Focus on education (Goal 4), which helps in raising awareness and education about various sustainable development issues.
- Bahrain has signed international agreements and treaties at various environmental, economic, and social levels, which help in benefiting from international expertise and grants to improve waste management.
- Raising awareness among elites in government bodies as well as the public about the 2030 SDGs plan.
- The national system for suggestions and complaints, “Tawasul” was established, which indicates the will to listen to the public, which in turn

will help in communication between the public and the leadership in everything related to improving waste management.

- Bahrain adopts a precautionary system in diversifying the economy.
- It stressed the need to reduce air pollution (Goal 6).
- Focus on public health and preventing pollution that harms humans (Goal 3).
- Bahrain emphasizes the provision of sustainable housing, which cares about waste sustainability per global best practices.
- The life expectancy of the population in Bahrain is 76.7 years, which means that Bahrain can benefit, in principle, from the benefits of this demographic dividend.
- Integration with the Gulf Cooperation Council countries represent a promising opportunity for improvement and growth.
- Focusing on promoting innovation represents a promising opportunity to improve waste management.
- In the Strategic Partnership Framework Project (2021-2024), Bahrain presented the development of an action plan for the management of electrical and electronic waste.
- Bahrain seeks to improve clean water infrastructure and reduce the environmental impacts of groundwater (Goal 6).
- Bahrain seeks to provide alternative energy sources through a partnership with the United Nations Development Program (Goal 7), which encourages consideration of converting waste to energy.

From the above, the achievements made by the Kingdom of Bahrain in achieving the SDGs are directly linked to improving waste management.

5.7 Link and synthesize findings to support overall conclusions.

By synthesizing the results of LCA, climate impact analysis, SDG alignment, stakeholder perspectives, survey data, and economic evaluations, this study confirms the suitability of the proposed “SELECT” model for sustainable MSWM in Bahrain. The LCA results identified composting and recycling as the most environmentally favorable options compared to landfilling, which poses serious climate and health risks through greenhouse gas emissions and leachate pollution. The survey findings revealed gaps in public awareness and practice, highlighting the urgent need for waste segregation and improved governance. The Stakeholder analysis emphasized the role of coordinated public-private partnerships, legal frameworks, and public engagement, while economic assessments supported the viability of composting and waste-to-energy systems with long-term savings and resource efficiency. These integrated findings directly align with and advance SDGs 11, 12, and 17, while revealing challenges in achieving SDGs 13 and 14 due to continued landfill reliance. Thus, the SELECT model emerges as a strategic, evidence-based framework rooted in environmental science, socio-economic dynamics, and policy alignment, providing a roadmap for sustainable waste management and inclusive development in Bahrain.

5.8 Study’s Recommendations

After completing this research and summarizing what the researcher concluded, the researcher presents his recommendations in these points:

- Assess the type and weight of each source-separated component to evaluate economic and environmental impacts.
- Control of MSWM can be improved through modern technologies.
- Investigate individual factors influencing knowledge, such as psychological and social factors.
- Initiate immediate waste reduction activities, like segregation and composting.
- Instill LCA in MSWM and continuously monitor environmental impacts.
- Develop performance indicators to measure MSWM success.
- Choose the appropriate technology for each waste type to maximize resources and reduce environmental harm.
- Enact a law for household waste segregation, involving different sectors.
- Develop indicators for waste types and recyclability to measure environmental impact.
- Study and select the best combination of MSWM scenarios based on practices.
- Adopt the proposed standards, administrative tools, and guidelines to support decision-making and SDGs.
- Increase community and institutional awareness of responsibilities under Public Hygiene Law No. 10 (2019), emphasizing the importance of waste classification, legal compliance, and active community engagement in sustainable waste management.

- Strengthen regional cooperation by establishing a GCC waste management network and aligning national strategies with regional public hygiene laws and agreements.
- Integrate social, behavioral, and institutional solutions with technical methods to address MSWM challenges.
- Design flexible and context-specific waste management strategies tailored to local conditions.
- Enforce strict penalties for non-compliance with proper waste handling, treatment, and disposal to reduce environmental pollution.
- Strengthen waste data management to inform effective policy design and support integrated regional research on MSWM in Bahrain and the GCC.

5.9 Publishing and Sharing Strategy

The main objective is to ensure that the thesis findings contribute to practical improvements in MSWM. This includes knowledge exchange, informing policy decisions, and building ongoing partnerships with government and local authorities. This project involves several key stakeholders, including the Ministry of Municipalities and Agriculture, the Supreme Council for the Environment, the local municipalities (Capital, Southern, Northern, and Muharraq), the Information and eGovernment Authority, and the Electricity and Water Regulatory Authority. Other relevant partners may include the UNEP in Bahrain and civil society organizations interested in environmental sustainability. The research proposes engaging with these stakeholders by preparing a policy brief, a two- to four-page summary that highlights the key findings and recommendations in a language accessible to decision-makers. A

more detailed executive summary report summarizing the methods, findings, and policy implications will be prepared, available in both print and digital formats. Closed-door presentations will be prepared, using professional presentations, through direct briefings for small groups with ministries and agencies. A collaborative national workshop will be held, inviting stakeholders to discuss the findings and their practical applications. Preparing local publications and articles in local government and environmental journals to raise awareness. Coordinating conferences to present the research at national or regional events to engage a wider audience. Community outreach by organizing local or online awareness events with civil society partners to promote sustainable waste management practices. Additionally, interviews, online surveys, and participatory workshops may be conducted with stakeholders. Their feedback will help refine the proposed SELECT model and make recommendations more practical and applicable. This process also enhances support and accountability among relevant institutions.

5.10 Research Limitation

The research was able to study the MSWM from a sustainability perspective using LCA. It was able to study specific aspects and cover the research objectives, although it is limited by some limitations, including:

- The study dealt with seven scenarios, each separately, in order to provide comprehensive knowledge to decision makers to know the best options and did not study more than one option at a time.
- The status of waste management was studied through literature and reports, and field visits were not conducted.

- The total cost was taken according to the average costs from different sources, and the costs were not taken according to what is within the limits of the study due to the lack of necessary information and data.
- The proposed LCA program was used, and no other program was used for comparison.

5.11 Future Research

The researcher suggests conducting some studies to cover the aspects that need to be covered and found important to delve deeper into the field of MSWM, as follows:

- Future research should also pay more attention to studying the mix of alternatives, as it not only identifies the environmental and economic impacts of waste but also offers multiple options depending on the available potential and may provide latent potential.
- LCA study of MSW can be conducted using the Social Life Cycle Assessment (SLCA) methodology to support decision makers in comparing products or services or improving the social impacts of the life cycle. This helps practitioners and researchers to understand the outstanding issues and needs to understand limitations of the role of SLCA in the context of life cycle sustainability.
- The study recommends conducting a study on the solutions and possibilities of cooperation between GCC countries to eliminate common challenges.
- These constants, administrative alternatives, tools, and opportunities need in-depth study, more accurate and detailed testing, and application to Bahraini society.

- Further research is needed into providing infrastructure to facilitate household waste separation and increase acceptance and participation in waste recycling.
- Given the volume of waste in the Kingdom of Bahrain and the clear gaps in evidence and knowledge, there is a great need for further research to guide future policies and actions to reduce waste in Bahrain.
- The study recommends conducting food waste research in the region, which can be done through collaboration between research centers, educational, and academic institutions across the GCC.

5.12 Contribution

This research is a good contribution to add to this knowledge on this important topic and to the literature of Bahrain.

This study is the first waste management study applying LCA in the Kingdom of Bahrain. Studies in the GCC countries have used LCA, but the OpenLCA tool distinguishes this study. Its importance lies in informing waste management stakeholders (including policy makers, scientists, etc.), compiling available data and research findings, pointing out current knowledge gaps, and identifying research needs.

The literature review mentioned in the study clearly shows that waste management research is still underrepresented in the GCC countries in general, and Bahrain is one of them. Moreover, the review and analysis of the available specialized literature shows that research focuses on environmental impacts and how to think about the future of the earth, future generations, and the need to take means and measures to reduce the negative impacts resulting from the current traditional management. One of the advantages of the

proposal presented by this study is its feasibility, as it is noted in the Kingdom of Bahrain that people love and cooperate in charitable works, and it is noted that sorting used clothes is a successful process and there is a great demand for it, so the chances of success of the idea of sorting MSW are greater.

5.13 Linking LCA with governance, innovation, and transformation management.

The research proposes integrating LCA in MSWM with governance theory, innovation diffusion, and transition management to enhance contributions to sustainability. LCA provides objective data on environmental, social, and economic impacts, supporting policy decisions. Transition management relies on multi-stakeholder collaboration and long-term planning, while innovation systems promote the adoption of practices like recycling and composting. Engaging stakeholders in this framework can drive the spread of environmental innovations. LCA data supports decision-making throughout transformation phases, as demonstrated in a Bolivia case study developing a new MSWM system through government-academic collaboration.

5.14 Summary of Chapter 5

This chapter synthesized the findings, confirming that the integration of environmental, economic, technological, and social dimensions within a life cycle approach offers a robust pathway toward sustainable MSWM. The chapter validated the proposed SELECT model as a comprehensive tool for guiding policy and planning decisions. In doing so, it reinforced the achievement of all four objectives and underscored the practical, theoretical, and policy contributions of the research.

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Appendices

Appendix A: Interview Questions

a. Interview with experts' questions

Interview with Experts of Waste Management

Aims:

This semi-structured interview is designed to be conducted with waste management professionals and experts. The interview questions will explore the following topics:

- 1- Exploring the three elements (energy - technology - cost efficiency) of the proposed SELECT model.
- 2- Exploring the extent of application of sustainable development goals (SDGs) in waste management in the Kingdom of Bahrain.
- 3- To determine the tools and alternatives available for decision-makers to create the best SWM policy that is cost-effective and environmentally friendly.
- 4- To determine the most crucial elements of appropriate technology (electronic system) to achieve the best environmental practices and sustainability of MSWM.

The suggested interview questions as follow:

1. What are the appropriate administrative tools and alternatives that support decisionmakers to determine the best SWM policy that leads to improved environmental outcomes at the lowest costs?
2. Do you think modern technology should be considered when thinking about developing a waste management process? How can technology be invested in waste management to be sustainable? (explain and suggest an electronic system or group of systems and applications to be applied to manage MSW)

3. How can Artificial Intelligence be employed in sustainable waste management? (technology)
4. Among the available techniques, and from your point of view, what are the appropriate technique for managing household waste in Bahrain? And why? (One container/two containers, one for organic materials and the second for the rest of the materials/multiple separate containers for each type)
5. What opportunities for waste management are available to enhance the environmental situation and cost efficiency?
6. Is Bahrain ready to treat separated waste materials? Why? What is the proposal?
7. Do you think that we should seriously consider utilizing waste to produce energy? What are the appropriate ways to invest in converting waste to energy in Bahrain?
8. Do you believe that cost effective is an important element in making any decision regarding waste management? What are the appropriate treatment methods for sustainable waste management with the highest economic efficiency? (Less cost and financial return instead of consumption and wasting money) (Suggest the appropriate method. Do you think one method, or multiple methods should be chosen)

مقابلة شبه منظمة مع خبراء إدارة النفايات

الأهداف:

تستكشف أسئلة المقابلة المواضيع التالية:

- 1- استكشاف العناصر الثلاثة (الطاقة – التكنولوجيا – الكفاءة الاقتصادية) لنموذج SELECT المقترح.
 - 2- استكشاف مدى تطبيق أهداف التنمية المستدامة في إدارة النفايات في مملكة البحرين.
 - 3- تحديد الأدوات والبدائل المتاحة لمتخذي القرار لخلق أفضل سياسة لإدارة النفايات الصلبة تكون فعالة من حيث التكلفة وصديقة للبيئة.
 - 4- تحديد أهم عناصر التكنولوجيا المناسبة (النظام الإلكتروني) لتحقيق أفضل الممارسات البيئية واستدامة إدارة النفايات الصلبة البلدية.
- أسئلة المقابلة المقترحة مع الخبراء هي:

1. ما هي الأدوات والبدائل الإدارية المناسبة التي تدعم متخذي القرار في تحديد أفضل سياسة لإدارة النفايات الصلبة وتؤدي إلى تحسين النتائج البيئية بأقل التكاليف؟
2. هل تعتقد أنه يجب أخذ التكنولوجيا الحديثة بعين الاعتبار عند التفكير في تطوير عملية إدارة النفايات؟ كيف يمكن استثمار التكنولوجيا في إدارة النفايات لتكون مستدامة؟ (شرح واقتراح نظام إلكتروني أو مجموعة أنظمة وتطبيقات من الواجب تطبيقها لإدارة النفايات الصلبة البلدية)
3. كيف يمكن توظيف الذكاء الاصطناعي في الإدارة المستدامة للنفايات؟
4. من بين التقنيات المتوفرة، ومن وجهة نظرك، ما هي التقنيات المناسبة لإدارة النفايات المنزلية في البحرين؟ ولماذا؟ (حاوية واحدة / حاويتين واحدة للمواد العضوية والثانية لبقية المواد / عدة حاويات منفصلة لكل نوع).
5. ما هي الفرص المتاحة لإدارة النفايات لتحسين الوضع البيئي وفعالية التكلفة؟
6. هل البحرين مستعدة لمعالجة النفايات المفصلة؟ لماذا؟ ما هو الاقتراح؟
7. هل ترى بأنه ينبغي التفكير جدياً في الاستفادة من النفايات في إنتاج الطاقة؟ ما هي السبل المناسبة للاستثمار في تحويل النفايات إلى طاقة في البحرين؟
8. هل ترى بأن الفعالية الاقتصادية عنصر مهم في اتخاذ أي قرار بشأن إدارة النفايات؟ ما هي طرق المعالجة المناسبة للإدارة المستدامة للنفايات بأعلى كفاءة اقتصادية؟ (أقل تكلفة وعائد مالي بدلاً من الاستهلاك وهدر المال) (اقترح الطريقة المناسبة، هل تعتقد أنه يجب اختيار طريقة واحدة أم طرق متعددة)

Appendix B : The questionnaire Survey

Questionnaire

Questionnaire for Assessing Sustainability of Municipal Solid Waste Management in the Kingdom of Bahrain.

Introduction:

The questionnaire aims to evaluate the sustainability of solid waste management, and to study the knowledge, attitude and application of community members to environmentally friendly standards and procedures in

waste management. This questionnaire aims to support decision makers to identify appropriate management strategies, opportunities and alternatives to determine the best solid waste management policies that enhance environmental outcomes while reducing costs. The social dimension is considered one of the pillars of sustainable development, which can be measured through a quantitative questionnaire.

This questionnaire is part of a doctoral study entitled: “Study of Municipal Solid Waste Management in the Kingdom of Bahrain: Applying Life Cycle Assessment and Sustainability” at the University of Bahrain.

Participation in the questionnaire is voluntary and takes around 5 minutes. The questionnaire data will be used for purely scientific research purposes and will be treated with complete confidentiality.

For inquiries, please contact the number 39144580 or email mahmood_afia@hotmail.com

Part 1: Personal Profile

Please circle the answers to the questions below:

Age	1. 18-20 years	2. 21-30	3. 31-40	4. 41-50	5. 51-60	6. 61 and above
Gender	1. Male		2. Female			
Educational Level	1. Intermediate and below		2. Secondary		3. Undergraduate	
	4. Postgraduate					
Marital Status	1. Single		2. Married		3. Others	
Nationality	1. Bahraini		2. Non-Bahraini			
Area of Living:	1. Northern		2. Southern		3. Muharraq	
	4. Capital					
Occupation						
Monthly Family Income	1. BD 300 and below		2. BD 301-900		3. BD 901-	

1500 4.BD1501 and above
Family Number 1. (2 persons) 2. (3-5 persons) 3. (6-8 persons) 4. (9 persons and above)
Place of Residence Type 1. House 2. Flat

Part 2: Questionnaire Statements

1. Measuring knowledge about municipal solid waste management and related issues

#	Statement	Totally True	True	Not Sure	Not True	Not True at all
1.	I know that there is a law regulating waste management in the country.					
2.	I know the meaning of “waste segregation”.					
3.	I know the meaning of “waste recycling”.					
4.	I know the meaning of “organic waste”.					
5.	The process of segregating and recycling waste in the right way benefits state economy.					
6.	The process of segregating and recycling waste in the right way benefits the environment					
7.	I think it is important for the government to enact a law that obliges the process of segregation of waste sources.					
8.	I am satisfied with the performance of Household Waste Management in the country					

2. Measuring the attitude to municipal solid waste management

#	Statement	Strongly Agree	Agree	Not Sure	Disagree	Strongly Disagree
1.	I am ready to segregate the waste at home if the municipalities request it and provide separate bins/skips to collect waste according to the type.					
2.	I support the idea of deploying containers to collect the recyclable wastes in residential neighborhoods					
3.	Waste management is a shared responsibility between regulatory authorities and all members of society.					
4.	I favor charging an additional fee for better management of household waste.					
5.	The importance household waste management shall be included in the educational curriculum and published through various media sources.					
6.	I am ready to cooperate with a program that contributes to awareness of the management of household waste.					
7.	I am ready to cooperate with a project led by civil society organizations to sustain waste management					
8.	The current method of collecting household waste is considered an environmentally friendly one.					
9.	I support the state's gradual enforcement of the mandatory segregation of waste at the sources.					
10	I support the use of technology in the management of household waste.					

2. Measuring Attitude about municipal solid waste management and related issues

3. Measuring Practice about municipal solid waste management and related issues

3. Measuring the practices of municipal solid waste management						
#	Statement	Always	Some times	Not Sure	Rarely	Never
11.	I advise others to put the residues in their proper places					
12.	I practice segregating household waste at home, such as food, plastic, glass, and paper.					
13.	I use multipurpose, environmentally friendly water bottles.					
14.	I consume less plastic because of its harmful effects on the environment.					
15.	I contribute to spreading environmental awareness in the community whenever I have the opportunity.					
16.	I use multipurpose, eco-friendly shopping bags.					
17.	I follow municipal regulations regarding disposal of household waste.					

Thank you for your kind cooperation, and I sincerely appreciate your gratitude.

الاستبيان باللغة العربية:

استبيان تقييم استدامة إدارة النفايات الصلبة البلدية في مملكة البحرين.

مقدمة:

يهدف هذا الاستبيان إلى تقييم استدامة إدارة النفايات الصلبة، ودراسة درجة معارف ومواقف وسلوك أفراد المجتمع للمعايير والإجراءات الصديقة للبيئة في إدارة النفايات. يهدف هذا الاستبيان إلى دعم صناع القرار في تحديد استراتيجيات الإدارة المناسبة والفرص والبدايل لتحديد أفضل سياسات إدارة النفايات الصلبة التي تعزز النتائج البيئية مع تقليل التكاليف. ويعتبر البعد الاجتماعي أحد ركائز التنمية المستدامة، ويمكن قياسه من خلال الاستبيان الكمي.

هذا الاستبيان هو جزء من دراسة دكتوراه بعنوان: “دراسة إدارة النفايات الصلبة البلدية في مملكة البحرين: تطبيق تحسين دورة الحياة والاستدامة” في جامعة البحرين.

المشاركة في الاستبيان طوعية وتستغرق حوالي 5 دقائق. سيتم استخدام بيانات الاستبيان لأغراض البحث العلمي والبحث وسيتم التعامل معها بسرية تامة.

للاستفسار يرجى الاتصال على الرقم 39144580 أو البريد الإلكتروني
mahmood_afia@hotmail.com

يرجى وضع دائرة حول إجابات الأسئلة أدناه:

العمر: 1. 18-20 سنة – 2. 21-30 سنة – 3. 31-40 سنة – 4. 41-50 سنة – 5. 51-60 سنة – 6. 60 فما فوق.		
الجنس 1. ذكر 2. أنثى		
المستوى التعليمي 1. المرحلة الإعدادية وأقل 2. الثانوي 3. المرحلة الجامعية 4. دراسات عليا		
الحالة الاجتماعية 1. أعزب 2. متزوج 3. أخرى		
الجنسية 1. بحريني 2. غير بحريني		
منطقة السكن 1. الشمالية 2. الجنوبية 3. المحرق 4. العاصمة		
الوظيفة		
مدخول الاسرة شهريا 1. BD 300 and below 2. BD 301-900 3. BD 901-1500 4. BD 1501 and above		
عدد أفراد الأسرة (1. شخصين (3-5) 2. أشخاص (6-8) 3. أشخاص (9) 4. أشخاص فما فوق)		
نوع مكان السكن 1. بيت 2. شقة		

1. قياس المعرفة لدى الناس حول إدارة المخلفات المنزلية وما يتعلق بها

الرقم	العبارة	صحيح تماما	صحيح	لست متأكدا	غير صحيح	غير صحيح أبدا
1.	أنا أعرف أنه يوجد قانون ينظم إدارة المخلفات المنزلية في البلد.					
2.	أنا أعرف المقصود بـ "فرز المخلفات".					
3.	أنا أعرف المقصود بـ "تدوير المخلفات".					
4.	أنا أعرف المقصود بـ "النفايات العضوية".					
5.	عملية فرز وتدوير النفايات بالطريقة الصحيحة تعود بالنفع على اقتصاد الدولة.					
6.	عملية فرز وتدوير المخلفات بالطريقة الصحيحة تعود بالنفع على البيئة.					
7.	أعتقد من المهم أن تسن الدولة قانونا يلزم عملية فرز المخلفات من المنازل.					

8.	أنا راض عن أداء إدارة المخلفات المنزلية في البلد.					
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2. قياس الاتجاهات لدى الناس فيما يتعلق بإدارة المخلفات المنزلية

الرقم	العبارة	أوافق بشدة	أوافق	لست متأكدا	لا أوافق	لا أوافق بشدة
9.	أنا على استعداد لفرز المخلفات في المنزل إذا طلبت البلديات ذلك.					
10	أنا أؤيد فكرة نشر حاويات إعادة التدوير في الأحياء السكنية.					
11	تعتبر إدارة المخلفات مسؤولية مشتركة بين المؤسسات التنفيذية وجميع أفراد المجتمع.					
12	أنا مع فرض رسوم إضافية مقابل تحسين إدارة المخلفات المنزلية.					
13	أنا أؤيد أن تقوم إدارة المخلفات المنزلية بنشر الوعي حول أهمية إدارة النفايات المنزلية في المناهج الدراسية وعبر مختلف وسائل الإعلام.					
14	أنا مستعد للتعاون مع أي برنامج يساهم في التوعية حول إدارة المخلفات المنزلية.					
15	أنا مستعد للتعاون مع أي مشروع بقيادة مؤسسات المجتمع المدني يساعد على استدامة إدارة النفايات.					
16	الطريقة الحالية لجمع المخلفات المنزلية تعتبر طريقة صديقة للبيئة.					
17	أنا أدم أن تبدأ الدولة تدريجيا في إلزامية فرز المخلفات من المنازل.					
18	أنا أؤيد استخدام التكنولوجيا في إدارة المخلفات المنزلية.					

3. قياس السلوك الدال على الوعي البيئي حول إدارة المخلفات المنزلية

الرقم	العبارة	دائما	أحيانا	لست متأكدا	نادرا	أبدا
19.	أنا أنصح الآخرين بوضع أنواع النفايات المختلفة في حاوياتهم الخاصة.					
20.	أنا أمارس فرز المخلفات المنزلية في المنزل، مثل الطعام، والبلاستيك، والزجاج، والورق.					
21.	أستخدم زجاجات مياه متعددة الاستخدامات وصديقة للبيئة.					
22.	أنا أستهلك كميات أقل من البلاستيك بسبب آثاره الضارة على البيئة.					
23.	أنا أساهم في نشر الوعي البيئي في المجتمع كلما أتحت لي الفرصة.					
24.	أنا أستخدم أكياس تسوق متعددة الاستخدامات وصديقة للبيئة.					
25.	أتبع الأنظمة البلدية فيما يتعلق بالتخلص من النفايات المنزلية.					

أشكركم على حسن تعاونكم، مقدرا جميل صنيعكم.

Appendix C: Successful countries' experiences in waste management

Country and Resource	Standards and Criteria	Cost-Effective
Germany (DW Akademie, 2013)	# Segregation. # Waste to energy. # There are seventy waste incinerators to generate energy. # The heat from burning waste is used to heat water to produce steam to generate electricity. # Converting the ash and sediment remaining after the	# It started with reuse, then turned into an industry that generates about four billion euros annually for the German economy. # The station generates electricity for about 20,000 homes and provides heating for about 10,000 homes.

	burning process into a type of cement used in paving streets. # The German government imposes a fine for non-compliance with this regulation. # There is a system for returning empty glass and plastic containers in exchange for a sum of money using machines designated to receive them. # Three-bin system: yellow: for plastics and metals, blue: for paper, grey: for bio-waste. # Glass containers and old clothes containers for all residents in each residential complex.	# The cost of building the station is about 150 million euros.
Osaka city, Japan (UNEP, 2017)	# The city has focused on health protection, greening and strict environmental planning. # Recycling system. # Burning waste to produce electricity. # Creativity in building a waste incinerator dazzles tourists. # Converting an ash dump on an island into a solar park. # Transforming the site of a former old landfill into a large city park and botanical garden, with a Dutch-style windmill and beds of tulips.	# To produce electricity for approximately 125,000 families in addition to municipal hot water.
Alappuzha city, India	# Decentralized waste management system. # Separate biodegradable waste and use it for	# Providing biogas for 174,000 people. # The city received the Clean City Award in 2016.

(UNEP, 2017)	composting and biogas cooking.	
City of Ljubljana, Slovenia	# Waste management based on the latest technologies. # Complete disposal of waste. # Recycling and reducing waste. # Relying on improvement and education. # Encourages people to separate waste. # The city relied on the recycling company to promote media campaigns. # A campaign to address all these problems is led by the Prime Minister. # The city became a leading political destination. # The city has become a sustainable tourist destination.	# Achieved the highest waste separation rates in Europe - more than 60% - # It received the “Green Capital” award from the European Communities in 2016. # The quantities of recovered materials increased from 16 kg/person in 2004 to 145 kg/person in 2014. # The amount of waste sent to the landfill decreased by 59%, and total waste decreased by 15%. # It achieved the lowest average waste management cost of €8 per household in one year.
Penang city, Malaysia	# It relies on food processing machines to transform waste into useful materials. # Transferring the remaining cups of rice through a machine to turn it into fertilizer for use in farmers’ fields. # Separation of waste at source is mandatory. # Converting food into fertilizer helps solve the methane problem.	# Food composting makes about 50% of the organic matter in waste composted, thus significantly reducing the number of landfills. # The cost of waste transportation and disposal is reduced. # Penang may receive funding from UN Environment's International Center for Environmental Technology, which has helped develop waste management policies.

Cajica City, Colombia	A recycling rate of 30% higher than the national average of 17%, # Cajica has adopted an ISWM policy. # Continuing awareness for five years, motivating families to separate their waste. # Benefiting from fertilization in greening, to be food for worms that are used in growing fodder. # Compost is produced from the decomposition of vegetables, which is rich in benefits and low in pollutants.	# Reduced landfill load by a quarter. # The city was selected as a case study by the United Nations through the promotion of its IWM program. # Transforming Colombia into a circular economy. # The city invests about 350 tons of organic waste for composting purposes.
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Appendix D: Organizations, Experts, and specialists in the field of LCA

1. The international expert's group on LCA for IWM.
2. The European Commission's Institute for Environment and Sustainability (IES).
3. ISPRA Joint Research Center (JRC-IES) Institute for Environment and Sustainability.
4. **JRC and DG INTPA:** JRC is an EC center, for science and knowledge research and provides scientific advice to EU policymakers. It develops LCA methodologies, sustainable development, climate, and innovation policies. Official website: <https://joint-research-centre.ec.europa.eu/>. The **DG INTPA** is a department of the European Commission responsible for

the design and implementation of the EU's international cooperation and development policies. It focuses on climate action, the green economy, and partnerships with developing countries. Official website: <https://international-partnerships.ec.europa.eu/>.

5. **Institute of Environment and Sustainability (IES):** provides scientific and technical support to EU policies for protecting the environment. Available at: [Institute of Environment and Sustainability \(IES\) — European Environment Agency \(europa.eu\)](#). [Accessed on May 18, 2024].
6. **Institute for the Environment and Sustainability (USA):** Its role is as an umbrella institute for undergraduate and graduate education and research on the environment and sustainability at Miami University. Available at: [Institute for the Environment and Sustainability, CAS | Miami University \(miamioh.edu\)](#). [Accessed on May 18, 2024].
7. **European Platform on LCA | EPLCA.** The EPLCA is the EU's knowledge base that responds to business and policy needs towards sustainable production and consumption. Available at: <https://eplca.jrc.ec.europa.eu/>. [Accessed on May 18, 2024].

ملخص الدراسة

تُعد إدارة النفايات الصلبة البلدية أمراً حيوياً للتنمية المستدامة وتحقيق أهداف التنمية المستدامة. تواجه البحرين ضغوطاً متزايدة، مما يتطلب استراتيجيات قائمة على الأدلة للحد من الضرر البيئي. مع ارتفاع النفايات العالمية من 2.1 مليار طن في عام 2023 إلى 3.8 مليار طن بحلول عام 2050، وتجاوز التكاليف 360 مليار دولار أمريكي، أصبح اتخاذ إجراءات عاجلة أمراً بالغ الأهمية.

تقترح هذه الدراسة نموذجاً شاملاً لإدارة مستدامة للنفايات الصلبة البلدية في البحرين. تُقيم الدراسة النظام الحالي، وتُقيم توافقه مع أهداف التنمية المستدامة، وتُحلل التحسينات المحتملة من عدة جوانب بيئية واقتصادية واجتماعية. تم تطبيق تقييم دورة الحياة (LCA) باستخدام OpenLCA على سبعة سيناريوهات معالجة، لقياس ست فئات من التأثير البيئي. واستُخدمت تكلفة دورة الحياة (LCC) لتقييم الجدوى الاقتصادية. كما أُجريت استطلاعات رأي عامة واستشارات مع خبراء لدمج وجهات نظر أصحاب المصلحة.

تُقدم الدراسة نموذج SELECT - وهو اختصار لـ Social, Environmental, Legislation, Energy, Cost-effectiveness, and Technology - كإطار عمل لتوجيه قرارات إدارة النفايات المستدامة. برز التسميد كأكثر أساليب المعالجة استدامة، يليه إعادة التدوير والتغويز. أظهرت البحرين أداءً قوياً في أهداف التنمية المستدامة 11 و12 و17؛ ومتوسطاً في الأهداف 3 و8 و9 و13 و15؛ وتقدماً ضئيلاً في الهدف 14.

تشمل الآثار العملية توجيه إصلاحات إدارة النفايات الصلبة البلدية، وتقليل ضغط مكبات النفايات، وتخفيف آثار المناخ، ودعم الاستراتيجيات الوطنية. كما يوفر البحث رؤى مقارنة بين الأنظمة الحالية والمحسنة فيما يتعلق بنتائج أهداف التنمية المستدامة. تشمل القيود التركيز على السياق الجغرافي للبحرين واستبعاد النفايات الخطرة والطبية وغير الرسمية نظراً لخصائصها الفريدة. استُخدمت البيانات المحلية كلما أمكن؛ وفي حالات أخرى، استُخدمت قواعد بيانات دولية مثل Ecoinvent. تُسهم هذه الدراسة في الحوارات العلمية والسياسية من خلال دعم صنع القرار، وتخطيط البنية التحتية، ورصد الاستدامة.

جامعة البحرين

كلية العلوم

برنامج البيئة والتنمية المستدامة



دراسة حول إدارة النفايات البلدية الصلبة في مملكة البحرين: تطبيق تحسين دورة الحياة والاستدامة.

رسالة مقدمة كجزء من متطلبات الحصول على درجة الدكتوراه في البيئة
والتنمية المستدامة

إعداد

محمود حبيب حسن العافية

الرقم الجامعي: 19921998

إشراف

د. محمد الانصاري

جامعة البحرين

مملكة البحرين

يونيو 2025