SCENARIO ANALYSIS OF MUNICIPAL SOLID WASTE MANAGEMENT OPTIONS FOR ABBOTTABAD CITY USING WASTE REDUCTION MODEL (WARM)

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2024

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

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Islamabad, Pakistan

2024

APPROVAL CERTIFICATE

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

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No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to SCEE (IESE) in partial fulfillment of the requirements for the degree of Master of Science in field of Environmental Engineering, School of Civil and Environmental Engineering, National University of Sciences and Technology, Islamabad.

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Dedication

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

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

Acknowledgements

To the highest God be glory great things He has done. I acknowledge Your great provisions, protections, and support throughout this course. I am thankful to my supervisor Dr. Musharib Khan for his appreciation, constructive suggestions, criticisms, and encouragement. My deep gratitude goes to him for giving his valuable time in department discussion and concrete suggestions to improve the research work and thesis write-up.

I remain indebted to the committee members, Dr. Rashid Iftikhar and Prof. Dr. Zeshan Sheikh for sparing time from their busy schedule for attending progress reviews and providing their beneficial suggestions and comments in the context of research and thesis. My appreciation goes to the entire faculty, the staff of IESE, and all my classmates for the support and guidance, they provided me during research.

My appreciation also goes to my parents, family, friends and colleague for their efforts, moral support, and suggestions towards my progress in life. I would like to specially thanks to my father for being eternal support, trust in my abilities, and stay with me in all highs and lows throughout this time.

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List of Abbreviation or Acronyms

AD	Anerobic Digestion
ADB	Asian Development Bank
CP	Composting
EPA	Environmental Protection Agency
ER	Energy Recovery
GHG	Greenhouse Gas
GWP	Global Warming Potential
I	Incineration
ISO	International Organization for Standardization
ISWM	Integrated Solid Waste Management
KPCIP	Khyber Pakhtunkhwa City Improvement Project
L	Landfill
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LFG	Landfill Gas
MBTU	Million British Thermal Unit
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
MTCE	Emission in Metric Ton Carbon Equivalent
MTCO2E	Emission in Metric Ton Carbon Dioxide Equivalent
OF	Open Flaring
R	Recycling
S	Scenario
ST	Short Ton
SW	Solid Waste
SWM	Solid Waste Management
TMA	Tehsil Management Authority
WARM	Waste Reduction Model
WASSA	Water and Sanitation Services Agency
WtE	Waste to Energy Facilities
SDGs	Sustainable Development Goals

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ABSTRACT

Abbottabad is one of the most beautiful cities in Pakistan. It is famous for its scenic landscapes and historical landmarks. It is a gateway to further tourist spots in Pakistan. While entering the city from Islamabad, Salhad dumping site is located at entrance of the city polluting Salhad stream flowing nearby due to leachate of the dumping site and causing unbearable order problem to the inhabitants and tourists. This dumping site is in use since 1984, however, the community and the legal institutions have increasingly started objecting against the improper management and disposal of solid waste. In this context, there is a dire need for a data-driven and environmentally sustainable solid waste management policy and program for hill stations. In this study, life cycle analysis of different waste management scenarios to identify the best option with the least environmental burden in terms of GHG emissions and energy consumption using US-EPA waste reduction model (WARM) was conducted. Comparison of seven proposed scenarios with the baseline solid waste management scenario was conducted. Baseline scenario was open dumping whereas in proposed scenario impact of composting, anerobic digestion, incineration, landfill and recycling was measured. Resultantly, scenario 8 was found to be the best one with not only least GHG emissions but also with second-least energy consumption. In this scenario, it was proposed that food waste (74.3% of total MSW) will be sent to composting facility and rest of the waste will be recycled, primarily comprising of mixed plastics, mixed metal, paper, glass, mixed electronics and concrete. Overall, the findings of this study suggest the incorporation of integrated solid waste management principles into planning and implementation of an environmentally sustainable solid waste management program for the city .

CHAPTER 1: INTRODUCTION

For centuries, humans have dealt with waste through various methods such as burning, discharging it into streams, storing it on the ground, or placing it in landfills. These practices have led to significant environmental issues, including air pollution from incineration, water contamination from direct discharge into streams, soil degradation from ground storage, and long-term ecological impacts from landfill use. Such methods not only harm the environment but also pose health risks to communities. The global population growth, technological advancements, and significant shifts in habits and lifestyle patterns over the past decades have led to a substantial increase in the generation rate of municipal solid waste (MSW) (Abubakar et al. 2022; Chen 2018).

Although the composition of waste varies globally, it typically includes both biodegradable and non-biodegradable components (Shafy and Mansour 2018). Managing municipal solid waste is a major challenge faced by both developing and developed countries in today's world (Zhang et al. 2024). Efficient waste management is essential for creating a better future. Common practices globally include open dumping, landfilling, biological treatment methods, and thermal treatment methods. Improper waste management can lead to significant economic and health problems for societies (Akmal and Jamil 2021).

In recent years, the interest in innovative and effective waste management strategies has been growing rapidly. This surge is driven by several factors, including the persistent challenges associated with landfill waste disposal, heightened environmental awareness among masses, and the increasing demand for the sources of alternative energy sources to replace fossil fuels. The environmental impact of traditional waste disposal methods has become more apparent, prompting communities and governments to seek sustainable alternatives. Furthermore, the need for renewable energy sources has led to innovations in waste-to-energy technologies, which not only help manage waste but also contribute to the generation of cleaner energy. This combination of environmental consciousness and technological advancement is fueling a shift towards more sustainable and efficient waste management practices worldwide.

Pakistan is currently facing a major energy crisis and many environmental and social problems due to poor municipal solid waste management (MSW). Both issues have reached alarming levels in Pakistan, similar to other developing countries (Safar et al. 2021). The annual production of solid waste in Pakistan is 30 million metric tons. This amount is expected to rise significantly in the coming years due to, increased urbanization, economic development and rapid population growth (Azam et al. 2020). Overall, approximately 50% of the generated waste is collected. However, this rate varies significantly depending on the locality. In larger cities, about 80% of the waste is collected, while in most rural areas, the collection rate is minimal. This discrepancy highlights the challenges faced in waste management infrastructure and services between urban and rural regions (Debrah et al. 2021). When it comes to waste disposal, properly managed landfill sites are almost absent.. In urban areas, waste is often left uncollected or is dumped in open spaces. Pakistan urgently requires a holistic waste management strategy to support policymakers in improving public health, minimizing land and water pollution, accurately measuring greenhouse gas emissions, and enhancing the country's environmental appeal.

1.1 Problem Statement of the Present Study

Abbottabad in Khyber Pakhtunkhwa in northwest Pakistan is a major tourist destination, providing a primary income source for residents. It is a gateway to northern areas via the Karakoram Highway and faces increasing urbanization and high municipal waste generation. Dumping municipal waste at the city entrance significantly detracts from the area's scenic beauty and contributes to serious health issues. This unsightly waste accumulation not only affects the visual appeal of the city, diminishing its attractiveness to visitors and residents alike, but it also poses health risks. The presence of waste can attract pests and generate harmful odors, leading to potential health hazards such as respiratory problems and other sanitation-related diseases. Consequently, both local residents and tourists are adversely affected, highlighting the urgent need for improved waste management practices to safeguard public health and preserve the city's aesthetic and environmental quality.

Effective and sustainable waste management is urgently needed. Despite economic challenges, addressing solid waste management is crucial due to its health implications.

Understanding the waste composition, which in Pakistan typically has a high organic and moisture content (55-60%), is essential for developing better management strategies. A financially viable and sustainable waste management solution must be identified to replace conventional methods.

Secondly, there is a lack of research focused on estimating the greenhouse gas (GHG) emissions resulting from different components of municipal solid waste (MSW) in Abbottabad. No studies have been conducted to analyze the scenarios of Municipal Solid Waste Management Options for Abbottabad City using the Waste Reduction Model (WARM) and specific contributions of various waste fractions to the overall GHG emissions in this region. This gap hinders the development of targeted waste management strategies that could effectively mitigate emissions and improve environmental sustainability in Abbottabad.

1.2 Objectives of the Study

Thus, based on the problem statement following are the specified objectives of the study:

1. To estimate the Green House Gas (GHG) emissions resulting from different components of solid waste of Abbottabad City
2. To conduct GHG accounting and estimate the net energy consumption of the baseline and proposed solid waste management scenarios of Abbottabad City

This research work is aligned with SDG 11 (Sustainable Cities and Communities) and SDG 13 climate action.

CHAPTER 2: LITERATURE REVIEW

Municipal solid waste (MSW) refers to the discarded by-products of everyday objects and materials used by individuals and households. Essentially, MSW encompasses all the refuse produced by daily human activities that need to be managed and disposed of properly. Municipal solid waste (MSW) is generated from a variety of sources, including households, commercial establishments, and healthcare facilities. This diverse mix of waste materials includes items such as furniture, tires, plastics, newspapers, packaging materials, containers, construction and demolition debris, as well as food and yard waste. Essentially, MSW is a composite of all the refuse produced through daily activities and operations across different sectors of society (Hayat and Sheikh 2016).

Data on municipal solid waste generation shows that 2.24 billion tons of waste were produced daily in 2020. Forecasts suggest that this figure is rising quickly and is anticipated to exceed 3.40 billion tons by 2050 (Shah et al. 2023).

By 2050, waste production in low-income nations is projected to increase threefold. At present, the Middle East and North Africa account for the lowest global waste generation at 6%, while East Asia and the Pacific contribute 23% of the total. However, regions such as South Asia, Africa, and the Middle East and North Africa are expected to experience a significant rise in waste generation, more than doubling by 2050 (Kaza et al. 2018). More than half of the waste in these regions is currently disposed of in open dumps. If this trend continues, it will have severe negative impacts on the environment, human health, and economic growth. This situation necessitates immediate and effective interventions to mitigate the detrimental effects and ensure sustainable waste management practices (Abubakar et al. 2022).

Urban infrastructure includes water supply, waste management, drainage systems, sewage services, power generation, transportation networks, telecommunications, street lighting, security, postal services, pedestrian pathways, and public green spaces. Solid wastes encompass any material that is considered worthless, unused, undesired, or discarded and exists in a solid form. Municipal solid waste, in particular, can include not only solid items but also semisolid food wastes and municipal sludge. These wastes are often the by-products of everyday activities in households, commercial establishments, and institutions (Adnan et al. 2020). Poor waste management significantly impacts the environment, health, and economy both globally and locally. Often, improper waste handling results in downstream costs that exceed the expenses of proper waste management.

Globally, numerous studies have explored the estimation of greenhouse gas (GHG) emissions from the waste sector through various modeling software programs. These studies have highlighted several challenges, including adjustments and constraints in methodologies, largely stemming from the scarcity of essential activity data needed from the waste sector. This limitation often hinders accurate assessments and necessitates adjustments in modeling approaches to compensate for data gaps. Researchers continue to address these challenges to improve the reliability and comprehensiveness of GHG emission estimations in waste management practices worldwide.

In 2022, Gadaleta et al. presented a study that employed the life cycle assessment approach to evaluate and compare the sustainability of different waste management plans. The study's methodology integrated multi-criteria decision analysis with Life Cycle Assessment, allowing for a comprehensive assessment of each plan's environmental impact. By using multi-criteria decision analysis, the study systematically considered multiple factors and criteria to rank and prioritize waste management strategies (Gadaleta et al. 2022).

Numerous optimization models have been developed to enhance the planning and management of municipal solid waste (MSW), utilizing diverse methodologies and techniques (Shaban et al. 2022). One approach involves constructing scenarios for complex and dynamic systems, offering practical guidelines to inform decision-making processes (Deus et al. 2017). In this context, the United States of America's Environmental Protection Agency developed the Waste Reduction Model (WARM), an optimized life cycle inventory (LCI) tool. It aids waste planners in modeling various scenarios and assessing their environmental impacts. The model's primary objective is to compare current baseline waste management strategies with alternative approaches, providing insights into potential improvements and guiding sustainable decision-making processes (Kucukvar et al. 2016).

Researchers have consistently identified landfills as a significant methane (CH_4) emission source. Avignon et al. (2010) highlighted the importance of local or city-scale greenhouse gas (GHG) inventories as critical benchmarks and tools for urban public policy. These inventories serve as essential instruments for assessing and managing urban environmental impacts, particularly concerning methane emissions originating from landfills (Avignon et al. 2010). Siddiqui et al. (2013) conducted an assessment of landfill gas (LFG) generation potential across various sites including Okhla (Delhi), Deonar and Gorai (Mumbai), Pirana (Ahmedabad), Uruli Devachi (Pune), and Autonagar (Hyderabad) using the Ecuador LFG Model. Their study revealed that Mumbai exhibited the highest potential for LFG recovery. However, they also acknowledged the challenges in accurately estimating LFG emissions and recovery potential due to constraints related to input data availability for the model. This limitation underscores the complexity and variability involved in predicting LFG outcomes across different landfill sites.

Jha et al. (2008) conducted a study on methane emissions from two landfills in Chennai, specifically Kodungaiyur and Perungudi. They employed both the Tier 2 First Order Decay (FOD) method and chamber methods to estimate the emissions. Their findings revealed discrepancies between the estimates obtained from the two methods, primarily due to the absence of specific site- and region-specific data. The study highlighted the importance of accurately determining the amount of municipal solid waste (MSW) delivered to landfills and understanding the generation and composition of methane at the source. These factors are crucial for reducing uncertainties in emission estimates and improving the reliability of methane emission assessments from landfills (Jha et al. 2008). Another study was conducted in Rasht City, Iran, evaluated and compared two methods for treating the organic component of municipal solid waste: composting and anaerobic digestion, focusing on environmental sustainability. Using the life cycle assessment method, researchers assessed the environmental impacts of both methods. The study analyzed 100 tons of municipal solid waste, considering all activities from transporting the waste to the production processes of each method. The findings showed that anaerobic digestion significantly reduced environmental damage compared to composting: 66.67% less impact on human health, 47.84% less on ecosystem quality, and 89.64% less on climate change. The results highlighted that anaerobic digestion of organic waste not only creates energy and value-added materials but also has substantial environmental benefits (Behrooznia et al. 2020).

In comparison to other regions, Pakistan has relatively limited research focused on greenhouse gas (GHG) inventories from the waste sector. However, a notable study by Batool and Chuadhry (2009) explored various waste management strategies for Lahore. Their research identified bio-gasification, single-material bank container systems for recycling, and energy recovery from landfill gas as environmentally viable options. These methods not only mitigate GHG emissions but also enhance the sustainability of waste management practices in Lahore, demonstrating the potential for significant environmental benefits in Pakistan through the adoption of these technologies (Batool and Chuadhry 2009).

Munir et al. (2015) conducted a study on municipal solid waste management in Ravi Town, Lahore, Pakistan, and reported a net global warming potential of 248,001,482.237 kg of CO_2 equivalent. The researchers highlighted bio-gasification as a promising solution to significantly reduce greenhouse gas emissions in the area. In addition to mitigating emissions, bio-gasification was also recognized for its potential to produce energy and compost, thereby providing a comprehensive approach to improving environmental sustainability and resource efficiency in waste management practices in Ravi Town (Munir et al. 2015). Mir et al. (2017) conducted an estimation of Pakistan's total greenhouse gas (GHG) emissions across various sectors, concluding that the country emitted 367 teragrams (Tg) of CO_2 equivalent. Within this total, the waste sector contributed 3% of the emissions. This finding highlights the significant, though smaller, role of waste management in the overall GHG emissions profile of Pakistan, emphasizing the need for targeted strategies to reduce emissions from this sector alongside other major contributors (Mir et al. 2017). In Pakistan, the generation of solid waste has been assessed to range between 0.28 and 0.61 kilograms per capita per day. This indicates a significant variation in waste production across different regions and populations. Additionally, the rate of solid waste generation is increasing at an annual growth rate of 2.4%. This steady rise underscores the escalating challenge of managing waste effectively as the population grows and urbanization progresses (Ilmas et al. 2018).

Land disposal of municipal solid waste (MSW) has been identified as the primary source of methane emissions in Pakistan's waste sector, accounting for 73% of the total CO_2 equivalent emissions. The remaining 27% of emissions originated from the disposal and treatment of industrial wastewater (Ilmas et al. 2018).

Hosseini and his coworker conducted the comparative Life cycle assessment of existing and proposed municipal solid waste management scenarios for Amol - Noor region of Iran using WARM model. Existing municipal solid waste management strategy primarily comprise on Landfilling (98.5%) and Recycling (1.46%) whereas proposed scenario was integrated one which includes Sources Reduction (14.7%), Recycling (7.3%), Landfill (6.5%), Combustion (8.3%) and Anaerobic digestion (63.3%). It was found that Proposed scenarios will reduce GHG emissions up to 202%. Constructing solid waste management plants with giving due consideration to the composition of solid waste would not be a fruitful strategy. Minimization of generation of waste, maximizing reuse and recycling, organic waste processing via composting and digestion, production of refused drive fuel for further using it in cement manufacturing plants and incineration facilities and ultimately disposing off in landfill the remaining less than 10% of waste was proposed solution for the improvement of current conditions. The implementation of this integrated solid waste management solution will eventually lead to prevent environmental and economic damages because of the degradation of valuable natural resources and discharge of various pollutants from landfills saving resources and energy (Hosseini et al. 2023).

Ahmad and his coworker conducted a study to measure the total GHG emissions accounting from different household activities including energy consumption, clean water production, wastewater and solid waste management using Intergovernmental Panel on Climate Change and Waste Reduction Model for Bintang Alam housing complex, Indonesia. The extremely significant GHG emission contributor was energy/ electricity sector and on second number was solid waste management. It was found that

GHG emissions would decline greatly via managing solid waste by composting and recycling practices as well as reducing consumption of electricity. It was found that the GHG emission would be reduced up to 26% if practices of composting and recycling were exercised together. (Ahmad and Kristanto 2021).

Deus et al. (2017) conducted a study to measure the environmental impact of integrating composting, recycling and hybrid model based on composting and recycling in the existing solid waste management strategy in the region of State of Brazil, Sao Paulo via waste reduction model for the simulation of energy use and greenhouse gas emissions in terms of carbon and carbon dioxide equivalent. The resultant findings showed that the recycling and composting would significantly reduce the greenhouse gas emissions and would increase the savings of energy. In addition, the best results were shown by the integrated solid waste management strategy comprise of composting and recycling. It would decline the 78.8% of greenhouse gas emissions and save energy up to 490.9% in comparison of baseline solid waste management scenarios. This study strongly encourage the municipalities for the creation of scenarios being a decision making and a planning tool to attain the target sets by the solid waste management policies (Deus et al. 2017).

Castigliego and his coworker conducted a study for the Boston City. They conducted a forward looking analysis under a zero waste strategy for the sector of solid waste via using Waste Reduction Model created by US EPA. It was found that the zero waste strategies implementation greatly reduce the burning of biomass and plastics in waste-to- energy combusting facilities along with the associated greenhouse gas emissions. This study found that the increase amount of renewabe would ultimately eliminate the greenhouse gas benefits percieved from the waste- to -energy combusting facilties whereas it has been considered that WtE are less carbon intensive than fossil based generation of electricity and other forms of waste treatment(Castigliego et al. 2021).

Due to spatial and temporal heterogeneity, the emissions analysis has been greatly complicated in the waste sector because of the significant contribution of indirect impact. For Instance, when assessing the impact of greenhouse gas of waste to energy combustion, it often includes credits for the emissions avoided by the use of organic waste to produce electricity, which replaces electricity that could have been generated from fossil fuels. However, as electricity grids become cleaner and rely less on carbon-based sources, this credit diminishes. Effective long-term emissions planning must consider these evolving factors to accurately evaluate the GHG reduction potential of various approaches for waste management.

This study highlights the importance of using a dynamic forecasting approach to understand the greenhouse gas impact of waste management choices. While waste- to-energy (WtE) combustion might currently seem more favorable than landfilling, the growing adoption of zero waste strategies and a cleaner grid will ultimately reduce its GHG benefits. In the end, the key to cutting emissions lies in diverting fossils fuel-based plastics waste from incineration.

Joseph and Prasad conducted a study which focuses on evaluating different scenarios using waste reduction model (WARM) to find the best and most sustainable municipal solid waste management solution Xangri-l´ a, a city in southern Brazil). A total of One hundred and fourteenth (114) scenarios were assessed, including options like recycling and landfilling with and without land fill gas recovery system, waste to energy technologies such as biogas recovery recovery from landfill, anerobic digestion and incineration. After simulating these scenarios in the WARM model, statistical methods were applied for data analysis. The findings suggest that increasing recycling rates should be the city's top priority as it offers the most sustainable and cost-effective approach. In the short term, collecting landfill biogas for the generation of energy is a practical option. For long-term solutions, implementing anerobic digestion and incineration technologies, especially through inter- municipal waste management partnership was recommended (Joseph and Prasad 2020).

2.1 Life Cycle Assessment

An LCA study is a tool that assesses the environmental impact of a product, process, or service by tracking the energy, materials used, and emissions released. It also helps identify opportunities for environmental improvements. The LCA methodology is an internationally recognized and standardized approach, widely regarded as one of the most effective tools for identifying and assessing the environmental impacts of different waste management options. This study uses the LCA framework, as defined by ISO standards (ISO 14040:14044). Multiple methods are applied together to assess system performance from various perspectives, including material and energy needs, environmental impacts, and ecologic al footprint. Concerning the scope of the assessment, nine different waste management strategies are examined. The collection process is not included in the analysis, as it is assumed to be the same across all scenarios.

2.1.1 Stages of LCA

A standard Life Cycle Assessment include four main stages: defining goal and scope of the study, compiling a life cycle inventory (LCI) that gathers data on energy, material usage and environmental emissions throughout the product or process lifecycle(following ISO 14041 guidelines), evaluating potential environmental impact (Life Cycle Impact Assessment, LCIA) based on resource use and emissions in line with ISO 14042 and finally interpreting the results from these stages to ensure they align with the objectives of the assessment (as per ISO 14043).

2.2. Waste Management Techniques

The methods used for waste management depends on the type of waste and how it is disposed of. These techniques can differ based on individual practices, location, time and the country. They include:

2.2.1. Recycling

Waste is collected from various locations and sorted based on the type of material for recycling. In the United States, robots are utilized for waste collection in the Baltimore River. In countries like Malaysia and Hong Kong recycling is implemented to manage and reduce construction waste (Wahi et al. 2016). Recycled municipal and construction waste is being repurposed to create eco-friendly geopolymer composites (Tang et al. 2020).

2.2.2. Composting

Organic waste is separated and left to decompose in a pit with the help of microbes over time. This process results in nutrient rich compost, which can be used as a natural fertilizer to improve soil fertility. Composting through biological methods boosts soil health, while vermicomposting not only reduce environmental impact but also increase the soil's nutrient content (Bhat et al. 2020). Vermicomposting is an effective method for promoting sustainable organic farming while also helping to maintain a balanced ecosystem (Kaur 2020). Black Soldier Fly Larvae were used to significantly reduce organic waste and speed up the composting process. The remaining material was then treated with E. Eugeniae, resulting in high quality vermicomposting (Bagastyo and Soesanto 2020). Vermicomposting of onion waste with cow dung creates a valuable nutrient rich resource for agriculture (Pallejero et al. 2020)

2.2.3. Landfilling

Landfilling refers to the practice of burying waste in the ground. To ensure safe and effective landfilling, proper procedures must be followed, including lining the base with protective materials and choosing areas with low groundwater levels. This process requires skilled personnel. In China, the installation of horizontal wells has been used to lower leachate levels in the landfills that contain municipal solid waste (Hu et al. 2020).

A model that utilizes physical, chemical and biological processes manages mercury Hg emission from landfills (Tao et al. 2020). The results of research on co-incineration of sewage sludge and municipal solid waste indicated that a greater amount of gaseous Hg^0 was converted in Hg^{2+} during the cooling phase which reduce environmental risk to the atmosphere (Sun et al. 2020).

2.2.4. Incineration

Incineration is combustion of waste at high temperature, and in order to prevent air pollution caused by combustion of waste, proper air filters are used. Anaerobic digestion was shown to be less preferable than direct burning as a sustainable technique of treating sludge (Hao et al. 2020). The technology of coal power plants combined with waste incineration method was regarded as a promising solution for waste disposal and conservation of fossil fuels (Ye et al. 2020). Degradation techniques as photocatalysis, hydrothermal, plasma, mechanochemistry, and biodegradation have demonstrated their effectiveness in purifying materials and are regarded as the best MSWI fly ash resource (Zhang et al. 2020).

2.2.5. Bioremediation

Bioremediation is a method that uses microorganisms and bacteria to remove contaminants, toxins, and pollutants from soil, water, and other environments. One of the primary threats to human health is the radioactive waste generated by power plants, and bioremediation is applied to help reduce these hazardous substances. Bioremediation technologies assist restore the natural state of soil and address the issue of heavy metal pollution (Saini and Dhania 2020). For the safe treatment and discharge of industrial wastewater, bioremediation is recommended as an affordable, efficient, and eco-friendly solution (Coelho 2020). Waste-to-energy (WtE) involves converting waste into usable forms of energy such as heat or electricity through initial waste processing. In China, anaerobic digestion has been effectively used for energy recovery and is proven to reduce environmental damage from greenhouse gas emissions associated with waste treatment (Zhang et al. 2020). Municipal solid waste (MSW) serves as a viable source of renewable energy that can be sustainably transformed into heat and electricity using WtE technologies like bio-methanation, incineration, pyrolysis, and gasification (Malav et al. 2020).

2.3. Greenhouse Gas Emissions

Municipal solid waste (MSW) can be a significant resource for generating electricity and reducing greenhouse gas (GHG) emissions. By utilizing MSW in waste-to-energy processes, such as incineration or anaerobic digestion, it is possible to produce electricity, which can help offset the use of fossil fuels and lower overall GHG emissions. Additionally, properly managed MSW can prevent methane emissions from landfills, further contributing to GHG reduction (Cheng and Hu 2010). Many developed nations have implemented municipal solid waste (MSW) management strategies centered on energy production. Common methods such as combustion, incineration, pyrolysis, and gasification are frequently employed to produce energy from MSW. These methods also produce combustible fuels such as methane and hydrogen (Azam et al. 2020). Initially, incineration was widely used to reduce the volume of municipal solid waste (MSW) and manage hazardous materials, although it was not primarily intended for energy recovery (Rahman and Alam 2020).

Greenhouse gas (GHG) emission estimates for the waste sector are reported in Pakistan's National Communication (ADB 2022; MOCC 2018) and the Nationally Determined Contribution (NDC) submitted to the UNFCCC (GoP 2021). As a signatory to the Paris Agreement, Pakistan has pledged to cut 20% of its projected GHG emissions by 2030, provided it receives international funding to cover the costs.

Abbottabad serves as a gateway to the breathtaking northern territories via the Karakoram Highway, while Mingora, Swat's largest city, leads to the magnificent valleys of Upper Swat, Kumrat, Chitral, and beyond. But Abbottabad's waste management system is severely hindered by administrative inefficiencies. A significant portion of the budget is consumed by salaries, leaving insufficient funds for necessary operational improvements. Even when transportation is available, it often fails to adhere to established schedules, resulting in inconsistent waste collection services. These issues contribute to the overall ineffectiveness of the waste management system, exacerbating environmental and public health challenges in the region. Abbottabad's Future Explosion of Solid Waste is an imminent danger that needs immediate attention and all-encompassing solutions to prevent a disaster for the environment and human health. To address this escalating situation, the city's government needs to make investments in cutting-edge waste management infrastructure a top priority, enforce administrative clarity, and raise community awareness.

2.4. GHG Emissions and Pakistan's Climate Vulnerability

Greenhouse gas (GHG) emissions, primarily from human activities such as deforestation, burning fossil fuels and industrial processes, trap heat in the atmosphere and are a major driver of climate change. As the concentration of GHGs increases, global temperatures rise, leading to rising sea levels, more extreme weather patterns, rising sea levels, and ecosystem disruptions. The relationship between GHG emissions and climate change is direct higher emissions lead to more intense climate impacts.

Pakistan is highly vulnerable to climate change, despite contributing relatively little to global GHG emissions. Its geographical location and reliance on agriculture make it particularly sensitive to changing weather patterns. Pakistan faces increasing risks from extreme events such as floods, droughts, glacial melt, and heatwaves. These threats endanger water resources, food security, and livelihoods, especially for poorer communities. Additionally, Pakistan's densely populated coastal areas and fragile infrastructure further increase its exposure to climate-related disasters. This vulnerability highlights the urgent need for mitigation and adaptation strategies to protect the country from the worsening effects of climate change.

In Abbottabad, municipal solid waste (MSW) management consists only of waste collection and open dumping at designated sites. The city's waste production exceeds the municipal authorities' capacity to manage it due to a lack of organizational framework, budget constraints, and a complex waste management system. To address these issues, an integrated waste management model is necessary. Life Cycle Assessment (LCA) is a valuable method for analyzing the environmental impacts of complete waste management systems. This research centers on the physical composition of municipal solid waste (MSW) in Abbottabad and evaluates its greenhouse gas (GHG) emissions and global warming potential (GWP) using the Waste Reduction Model (WARM).

Once the waste has been collected, data on its volume and composition must be acquired. The data can then feed into the waste management strategy and give the information needed by GHG inventory compilers to estimate historical and anticipated emissions from the waste sector. In this Waste Reduction Model (WARM), evaluation factors that are crucial for quantifying different waste management activities, such as waste reduction percentage, recycling rates, composting rates, landfilling, incineration, and energy generation through digestion are measured. This method computes greenhouse gas (GHG) emissions and energy savings derived from recycling under current waste management practices and potential scenarios. It also assesses how each scenario would impact waste management by measuring reductions in emissions and energy conservation. Ultimately, these calculations determine the effectiveness of each strategy in managing waste efficiently.

GHG savings are determined by comparing the emissions linked to the alternative scenario. In this context, the emissions related to the baseline scenario cannot simply be calculated by multiplying the quantity by an emission factor (Hassan et al. 2019). In this context, the application of WARM energy factors necessitates the consideration of two distinct scenarios. The baseline scenario reflects existing waste management practices, while the alternative scenario proposes a different approach. By analyzing these scenarios, it becomes feasible to quantify the energy consumption associated with current practices and compare it with the potential energy savings achievable through alternative methods. This comparative analysis not only helps evaluate the environmental impact of different waste management strategies but also informs decision-making aimed at enhancing resource efficiency and reducing overall energy consumption in waste management processes. Based on this analysis, the difference between the alternative scenario and the baseline scenario is calculated. This difference indicates the amount of energy either consumed or avoided due to the alternative management scenario. It serves as a measure of the potential energy savings or additional consumption associated with adopting different waste management practices. Understanding this difference is crucial for assessing the effectiveness of alternative strategies in reducing energy use and improving overall resource efficiency in waste management systems (Hassan et al. 2019).

CHAPTER 3: METHODOLOGY

3.1. Waste Reduction Model (WARM)

In this study, Waste Reduction Model version 16 has been used as life Cycle Assessment tool which is created by Environmental Protection Agency of United States of America. It is excel- based tool. Emission and economic factor updated regularly by US EPA due to which now there are 16 versions of this tool. Solid waste planners and organizations can evaluate the economic effects and reductions in greenhouse gas (GHG) emissions from various waste management techniques by using the Waste Reduction Model using life cycle Assessment Approach which includes Source Reduction, Landfilling, combustion Recycling, Composting and Anerobic Digestion. This model calculates following parameters for baseline waste management and alternative waste management practices mentioned above.

- Emissions in metric tons carbon dioxide equivalent ($MTCO_2E$)
- Emissions metric tons carbon equivalent (MTCE)
- Energy consumption in millions of BTUs (MMBTU)
- Tax impacts, wage impacts and labor hours

Warm recognized 61 different materials found in municipal solid waste stream from plastic to paper to organics. To run the model the input required by the model is

1- Composition of waste in short ton component-wise as per existing categories of waste in the model

2- Distance from collection point to treatment facility in miles

3- Quantity of waste destined for each treatment option separately

In addition, other inputs are specific to respective waste management practices as mentioned below.

- **Landfill:** Landfill type (landfill without landfill gas control system, landfill with landfill gas control system for energy recovery and open flaring), landfill gas collection efficiency (typical, worst case, California or aggressive), moisture condition and associate bulk municipal solid waste decay rate-K(dry, moderate, wet, bioreactor) to describe the average condition at landfill

- **Anerobic digestion:** type of anerobic digestion (wet or dry), land application of digestate (after curing or without curing)
- **Recycling:** Current mix or 100% virgin

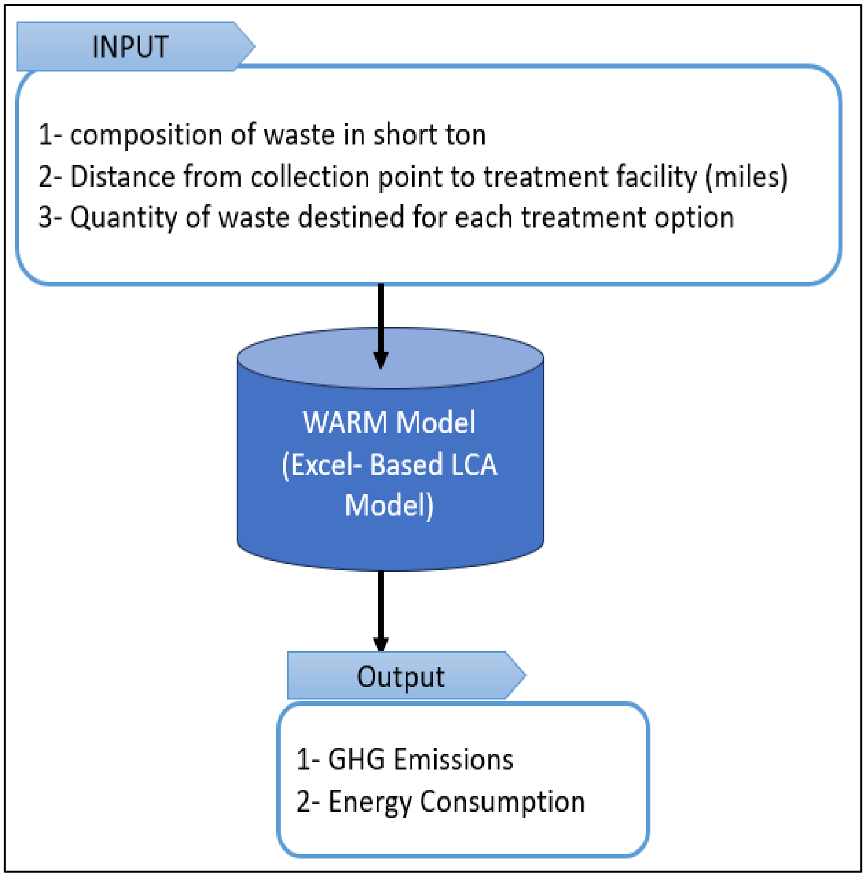

Figure 3.1. WARM Model

In this study, as explained in chapter 1, only GHG emission in metric ton of CO_2 Equivalent and energy consumption in million British thermal unit will be measured. Economic analysis is not included. Figure 3.2 is showing the user interface where a user can enter inputs in the WARM model. Figure 3.3 and 3.4 is showing user interface where a user can see the results in term of GHG emission analysis and energy analysis respectively.

Version 16

Waste Reduction Model (WARM) -- Inputs

Use this worksheet to describe the baseline and alternative waste management scenarios that you want to compare. The blue shaded areas indicate where you need to enter information.
Please enter data in short tons (1 short ton = 2,000 lbs.)

1. Describe the baseline generation and management for the waste materials listed below. If the material is not generated in your community or you do not want to analyze it, leave it blank or enter 0. Make sure that the total quantity generated equals the total quantity managed.

2. Describe the alternative management scenario for the waste materials generated in the baseline. Any decrease in generation should be entered in the Source Reduction column. Any increase in generation should be entered in the Source Reduction column as a negative value. Make sure that the total quantity generated equals the total quantity managed.

Material Type	Material	Tons Recycled	Tons Landfilled	Tons Combusted	Tons Composted	Tons Anaerobically Digested	Tons Generated	Tons Source Reduced	Tons Recycled	Tons Landfilled	Tons Combusted	Tons Composted	Tons Anaerobically Digested	
Paper	Corrugated Containers				NA	NA	0.00					NA	NA	
	Magazines/Third-class Mail				NA	NA	0.00					NA	NA	
	Newspaper				NA	NA	0.00					NA	NA	
	Office Paper				NA	NA	0.00					NA	NA	
	Phonebooks				NA	NA	0.00					NA	NA	
	Textbooks				NA	NA	0.00					NA	NA	
	Mixed Paper (general)				NA	NA	0.00					NA	NA	
	Mixed Paper (primarily residential)		11,232.64		NA	NA	11,232.64					NA	NA	Tons manage
	Mixed Paper (primarily from offices)				NA	NA	0.00					NA	NA	
Food Waste	Food Waste	NA		64,601.86			64,601.86		NA					Tons manage
	Food Waste (non-meat)	NA					0.00		NA					
	Food Waste (meat only)	NA					0.00		NA					
	Beef	NA					0.00		NA					
	Poultry	NA					0.00		NA					
	Grains	NA					0.00		NA					
	Bread	NA					0.00		NA					
	Fruits and Vegetables	NA					0.00		NA					
	Dairy Products	NA					0.00		NA					
	Yard Trimmings	NA					0.00	NA	NA					

User's Guide | Analysis Inputs | Summary Report (MTCO2E) | Analysis Results (MTCO2E) | Production + EOL (MTCO2E) | Summary Report (energy) | Ar ...

Figure 3.2. User interface of WARM for Data Input

GHG Emissions Analysis -- Summary Report

Version 16
GHG Emissions Waste Management Analysis for
Prepared by:
Project Period for this Analysis: 01/00/00 to 01/00/00

Note: If you wish to save these results, rename this file (e.g., WARM-MN1) and save it. Then the "Analysis Inputs" sheet of the "WARM" file will be blank when you are ready to make another model run.

GHG Emissions from Baseline Waste Management ($MTCO_2E$): 6,265.72

Material	Tons Recycled*	Tons Landfilled	Tons Combusted	Tons Composted	Tons Anaerobically Digested	Total $MTCO_2E$
Mixed Paper (primarily residential)	-	11,232.64	-	NA	NA	14,901.78
Food Waste	NA	-	64,601.86	-	-	(8,832.98)
Mixed Plastics	-	8,959.59	-	NA	NA	159.36
Mixed Electronics	-	189.42	-	NA	NA	3.37
Mixed Metals	-	75.77	-	NA	NA	1.35
Glass	-	710.33	-	NA	NA	12.63
Concrete	-	1,136.52	NA	NA	NA	20.21
						0
						0
						0

Figure 3.3. User Interface of WARM for Output- GHG Emission Analysis

Energy Analysis -- Summary Report

Version 16
Energy Waste Management Analysis for
Prepared by:
Project Period for this Analysis: 01/00/00 to 01/00/00

Note: If you wish to save these results, rename this file (e.g., WARM-MN1) and save it. Then the "Analysis Inputs" sheet of the "WARM" file will be blank when you are ready to make another model run.

Energy Use from Baseline Waste Management (million BTU): (141,027.96)

Material	Tons Recycled*	Tons Landfilled	Tons Combusted	Tons Composted	Tons Anaerobically Digested	Total Million BTU
Mixed Paper (primarily residential)	-	11,232.64	-	NA	NA	2,653.96
Food Waste	NA	-	64,601.86	-	-	(146,297.84)
Mixed Plastics	-	8,959.59	-	NA	NA	2,116.90
Mixed Electronics	-	189.42	-	NA	NA	44.75
Mixed Metals	-	75.77	-	NA	NA	17.90
Glass	-	710.33	-	NA	NA	167.83
Concrete	-	1,136.52	NA	NA	NA	268.53

Figure 3.4. The User Interface of WARM for Output- Energy Analysis

3.2. Study area selected for present study

The area selected for this particular study is District Abbottabad. Abbottabad is located in the province of Khyber Pakhtunkhwa in northwest Pakistan, It is a major tourist destination, providing a primary income source for residents. It is a gateway to northern areas via the Karakoram Highway and faces increasing urbanization and high municipal solid waste generation. Figure 3.5 is showing map of the area.

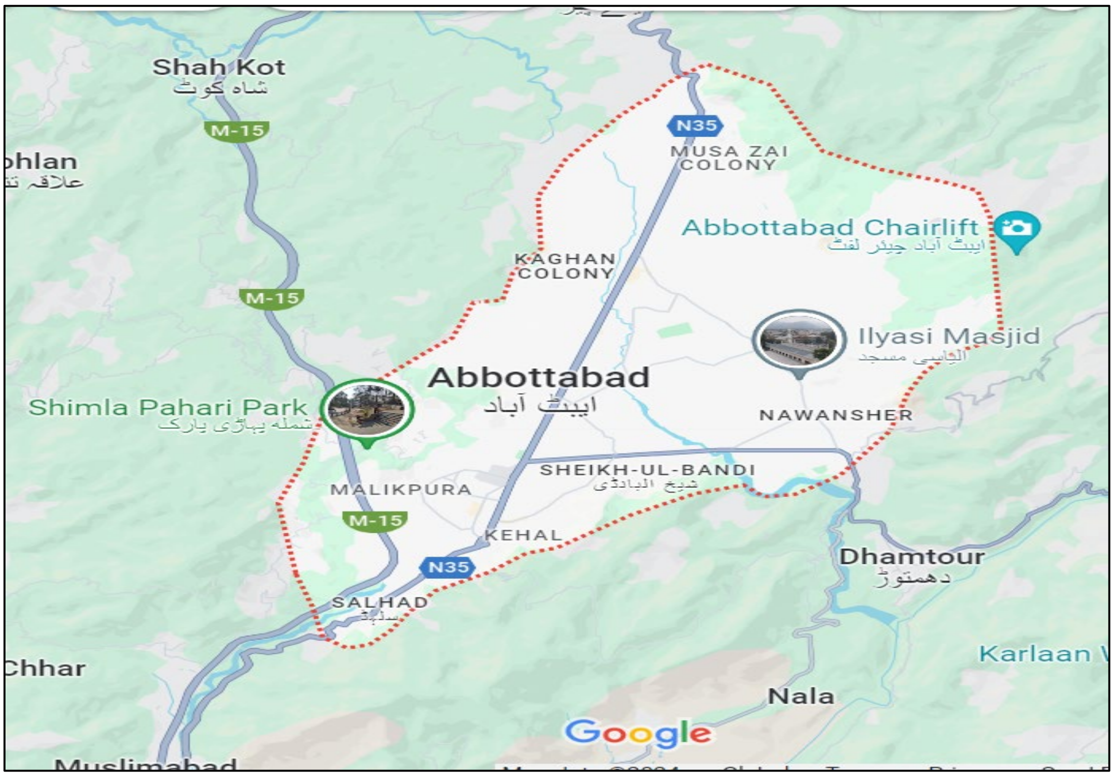

Figure 3.5. Map of the Study Area

The population of the district Abbottabad is 1332912 persons and 1967 square Kilometer. (Census 2017). It consists on ten union councils Malik Pura, Central urban, Kehal Urban, Nawa Sher Urban, Mirpur, Kakul, Dhamtour, Salhad, Jhangi, Sheikhul Bandi, Banda Pir Khan and Baldheri. District Abbottabad is famous for its scenic beauty and historical landmarks. The famous tourist spots are St.Luke's church, Shimla Peak, Lodge of Civil Surgeon of Hazara, Sajikot Waterfall, Dhamtour village, Jalal Baba Auditorium Complex, Old Lockhart House (Constructed by Sir William Lockhart, Harnoi Lake, Kala Pani, Musa ka Musala, Ilyasi Mosque, Lady Garden Public Park, and Thandiani as shown in the Figure 3.6

Figure 3.6. Breathtaking View of Abbottabad (Abbottabad 2014)

Salhad dumping site is located at the city entrance and Salhad water stream is following nearby. Dumping municipal waste at the entrance of the city significantly detracts from the area's scenic beauty and contributes to serious health issues. This unsightly waste accumulation not only affects the visual appeal of the city, diminishing its attractiveness to visitors and residents alike, but it also poses health risks.

Figure 3.7. Dumping Site of Abbottabad- Salhad Dumping Ground (The News 2023)

The presence of waste can attract pests and generate harmful odors, leading to potential health hazards such as respiratory problems and other sanitation-related diseases. Consequently, both local residents and tourists are adversely affected, highlighting the urgent need for improved waste management practices to safeguard public health and preserve the city’s aesthetic and environmental quality.

3.2.1. Waste generation rate of Abbottabad

Total daily solid waste generation is 216 tons per day. Table 3.1 shows showing Union Council-wise solid waste generation rate per day. In addition, authorities or organizations responsible for the collection and management of solid waste of the city are the Water and Sanitation Services Agency Abbottabad (WASSA), Abbottabad Cantonment Boards, and Tehsil Management Authority.

Table 3.1. Solid Waste Generation Rate of Abbottabad

S.No	**Union Councils**	**Waste (t/d)**
1.	Malik Pura	14.70
2.	Central urban	14.54
3.	Kehal Urban	14.48
4.	Nawa Sher Urban	32.55
5.	Mirpur	29.33
6.	Kakul	10.50
7.	Dhamtour	9.59
8.	Salhad	23.63
9.	Jhangi	14.70
10.	Sheikhul Bandi	18.38
11.	Banda Pir Khan	18.90
12.	Baldheri	14.44
	Total	**216**

Source: (GoP and ADB 2021)

3.2.2. Dumpsite/Waste Treatment Facilities in Abbottabad

The Salhad dumping region, which consists of over 100 canals and can hold 183 metric tons of solid waste per day, is where WSSCA now dumps MSW. Usage of the site dates back to 1984. The nearby stream, Salhad stream, is being contaminated by the waste's leachate and the smell, which is upsetting the local population. A new site at Dhamtor had been acquired for the dumping point, but funding and project completion were dependent on the Khyber Pakhtunkhwa Cities Improvement Project (KPCIP).

3.3. Goal and Scope of the Study

The goal of the study is to evaluate the impacts of various waste management scenarios for District Abbottabad using environmental indicator of Green House Gas Emissions and energy consumption. The tool was chosen as a support method to estimate the effects of different waste management techniques using the Gate to Grave approach for Abbottabad.

3.3.1. Functional Unit of the Study

While conducting a life cycle assessment, a functional unit is one of the key elements to determine the way forward. The functional unit could be characterized as an evaluation of the Product System's functional outputs, and it offers a benchmark against which inputs and outputs can be compared. The functional unit will also serve as a benchmark for comparison with other systems or scenarios. Otherwise, it will be impossible to compare LCA studies in a fair and equal manner. Waste management modeling in this study for district Abbottabad municipality was limited to waste generation for one year. In this way, an input of 86906.12 short metric ton of waste was considered.

3.3.2. System Boundary of Study

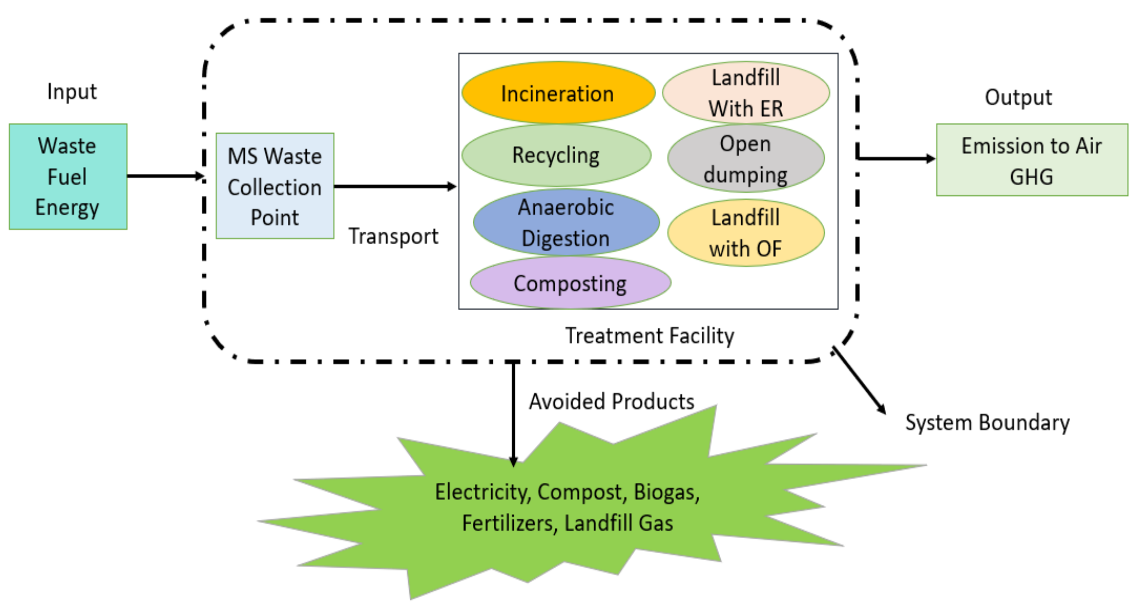

Figure 3.8. System Boundary

3.3.3. Life Cycle Inventory

Reviews of the literature, surveys, and the US EPA WARM (version 16) library were the main sources of information for establishing the inventory. The library was used to source detailed information about emissions to air and water, as well as thorough data about material and energy inputs and outputs for processes like transportation, electricity mix, unsanitary landfill, recycling, sanitary landfill, anaerobic digestion, industrial composting, and incineration.

3.3.4. Waste Composition

As per a report published by the Asian Development Bank following is the waste characterization data of the district Abbottabad (ADB 2022).

Table 3.2. Composition of Solid Waste of District Abbottabad

S.No	Component of MSW	Weight (%)
1.	Kitchen Green waste	66.74
2.	Dry Grass and wood	1.47
	Paper	11.86
3.	Plastic	9.46
4.	Bottle and Glass	0.75
5.	Metal	0.08
6.	Domestic Hazardous Waste	0.2
7.	Ceramic, Stone, Soil etc.	1.15
8.	Sieve Remaining	0.05
9.	Textile	1.78
10.	Leather and Rubber	1.07
11.	others	5.39

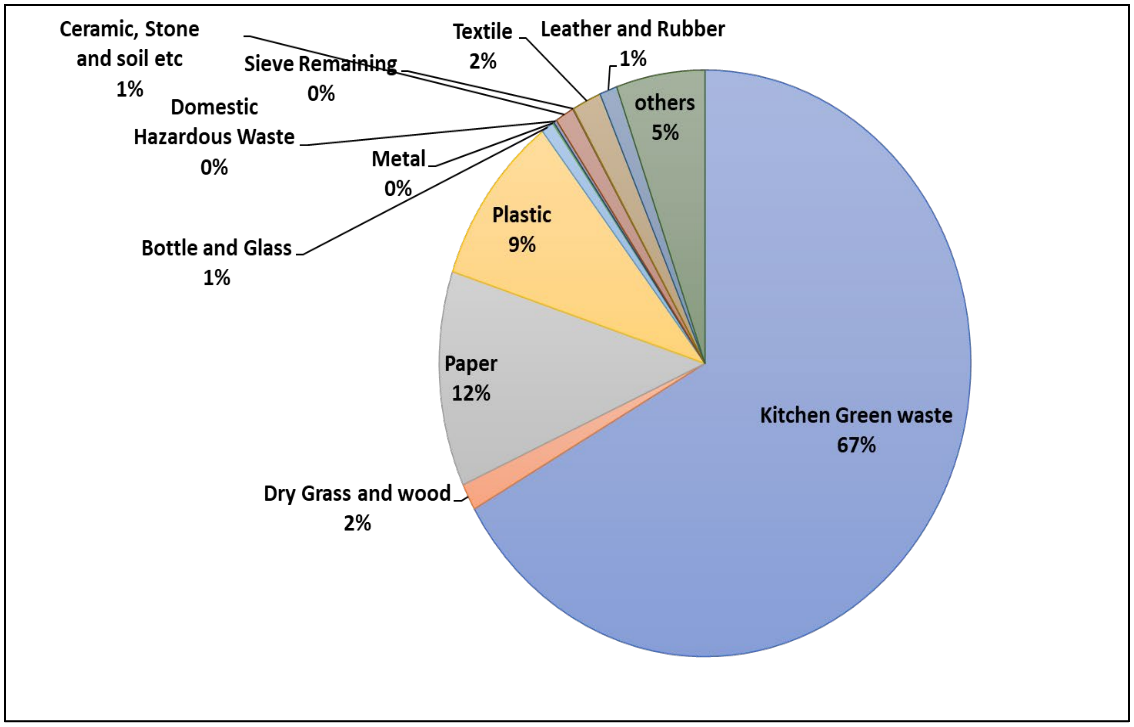

Figure 3.9 Percentage Composition of MSW of Abbottabad (ADB 2022)

The scenarios analyzed in this study were derived from the gravimetric composition of municipal solid waste (MSW) in the specified city, as the WARM model requires detailed data on the proportion of each material present in the waste stream. A few things were taken into account for the modeling;

1) Kitchen and green waste were grouped in the category of food waste.
2) Dry grass and wood material were clumped in to Yard Trimming
3) Paper, plastic, metal, domestic hazardous waste, bottle and glass were included in paper (primarily residential) mixed plastic, mixed metal, Mixed Electronics and glass category respectively.
4) Sieve remaining, ceramics, stone, and soil are grouped into the category of concrete, a subcategory of construction materials.

Since rubber, textiles, and leather cannot be classified as recyclable garbage or as organic matter that decomposes naturally, they were not taken into consideration.

Thus, Table 3.3 displays the material composition and classes utilized in the modeling.

Table 3.3. Composition of MSW used in WARM model

S.No	Component of MSW	Weight (%)
1.	Food Waste	72.7
2.	Yard Trimming	1.6
3.	Paper (Primarily Residential)	12.9
4.	Mixed Plastic	10.3
5.	Glass	0.8
6.	Mixed Metals	0.1
7.	Mixed Electronics	0.2
8.	Concrete (construction material)	1.3

3.3.5. Scenario Modeling for Life Cycle Assessment

Table 3.4. Scenario Modeling for Life Cycle Assessment

Type of waste and % Composition	Waste Management Scenarios								
	S1	S2	S3	S4	S5	S6	S7	S8	S9
Food Waste	Baseline Scenario – Open Dumping	Landfill with LFG for Energy Recovery	Landfill with LFG for Open Flare	AD	CP	I	L	L	CP
Paper				L	L	L	I	R	R
Mixed Plastic				L	L	L	I	R	R
Glass				L	L	L	L	R	R
Mixed Metals				L	L	L	L	R	R
Mixed Electronics				L	L	L	L	R	R
Concrete				L	L	L	L	R	R

Table 3.4 shows the different waste management scenarios modeled for the Life Cycle Impact Assessment. S1 is existing solid waste management scenario whereas S2 to S8 are proposed alternate solid waste management scenarios. AD is anaerobic digestion, L is landfill without landfill gas control system, I represent Incineration, CP is composting and R is recycling.

Scenario 1: Open Dumping

Scenario 1 is a baseline solid waste management scenario in which 100% of the Municipal solid waste is openly dumped in the Salhad dumpsite

Scenario 2- Landfill with LFG for Energy Recovery

Scenario 2 is a proposed municipal solid waste management scenario in which 100% of the Municipal solid waste was considered to be landfill having a proper landfill gas control system in which landfill gas would be recovered and used further to generate electricity.

Scenario 3- Landfill with LFG for Open Flaring

Scenario 3 is proposed municipal solid waste management scenario in which 100% of the Municipal solid waste was considered to be landfilled having a proper landfill gas control system in which landfill gas would be recovered for open flaring.

Scenario 4- Anaerobic Digestion for Food Waste

Scenario 4 is proposed municipal solid waste management scenario in which only food waste 74.3% of the total waste was considered to be anaerobically digested in the wet anerobic single-stage, mesophilic digester. Rest of solid waste comprising on paper 12.9%, plastic 10.3%, glass 0.8%, metal 0.1%, electronics 0.2% and concrete 1.3% was considered to be landfill without landfill gas recovery system for energy recovery or open flaring.

Scenario 5- Composting for Food Waste

Scenario 5 is proposed municipal solid waste management scenario in which only food waste 74.3% of the total waste was considered to be composted in Central composting facility. Rest of solid waste comprising on paper 12.9%, plastic 10.3%, glass 0.8%, metal 0.1%, electronics 0.2% and concrete 1.3% was considered to be landfill without landfill gas recovery system for energy recovery or open flaring.

Scenario 6- Incineration for Food Waste

Scenario 6 is proposed municipal solid waste management scenario in which only food waste 74.3% of the total waste was considered to be combusted in a mass burn facility.

Rest of solid waste comprising on paper 12.9%, plastic 10.3%, glass 0.8%, metal 0.1%, electronics 0.2% and concrete 1.3% was considered to be landfill without landfill gas recovery system for energy recovery or open flaring.

Scenario 7- Incineration for Combustible Materials (Paper and Plastics)

Scenario 7 is a proposed solid waste management scenario in which combustible materials paper 12.9% and plastic 10.3% were sent to the incinerator and the rest of the waste (76.8% of the total municipal solid waste) was landfill without any landfill gas recovery system which included glass 0.8%, metal 0.1%, electronics 0.2% concrete 1.3% and food waste 74.3%.

Scenario 8- Recycling for Recyclables

Scenario 8 is a proposed solid waste management scenario in which recyclable materials are 25.7% of the total municipal solid waste which includes paper 12.9%, plastic 10.3%, glass 0.8%, metal 0.1%, electronics 0.2% and concrete 1.3% sent to open and closed loop recycling and rest of waste, food waste 74.3% of the total municipal solid waste was landfill without any landfill gas recovery system.

Scenario 9- Integrated Solid Waste Management

In this scenario, 74.3% of total municipal solid waste, comprising mainly of food waste (organic fraction) was considered to be composted and the rest of the 25.7% of total municipal solid waste, comprising mainly on recyclable (inorganic and inert materials), comprising mainly on paper, plastic, glass, metal, electronics, and concrete was considered to be recycled. Concrete and Mixed Electronic materials are modeled as open-loop recycling processes in WARM. The materials glass, paper, plastic, and metal are modeled as close-loop recycling processes in WARM. Whether you model a material in a closed-loop or open-loop process depends on the most common method of recycling the material.

3.3.6 Key Assumption Regarding Solid Waste Management Technologies

a. Open Dumping

In this study, open dumping means waste is simply dumped on the open ground /area without any landfill Gas (LFG) Control or recovery System,

b. Landfilling

Landfill (Energy Recovery/ER)

This terminology refers to landfill sites where waste is disposed has a proper Landfill Gas Control System methane is recovered through a proper energy recovery system to generate electricity

Landfill (LFG Through Flare)

This terminology refers to landfill sites where waste is disposed has a proper Landfill Gas Control System methane is flared

Landfill Gas Collection Efficiency

The effectiveness of landfill gas collection varies during the course of the landfill's life in the case of gas-recovery landfills. A variety of collections have been estimated and utilized in the WARM tool for a number of distinct landfill situations, drawing from a review of the literature on field measurements and expert discussion.

S.No	Different landfill scenarios	Landfill Gas Collection Efficiency (%)
1.	Typical	Years (0-1)- 0%, Years (2-4)-50%, Years(5-14)-75, Years (15 -1 year before final cover)-82.5%, Final cover 90%
2.	Worst- Case	Years (0-4)- 0%, Years (5-9)-50%, Years (10-14)-75%, Years(15-1 year before final cover) 82.5%, Final cover 90%
3.	Aggressive	Year (0)-0%, Years(0.5-2)-50%, Years (3-14)-75%; Years(15-1 year before final cover)-82.5%, Final cover 90%
4.	California	Year (0)-0%, Year (1)-50%, Years (2-7)-80%, Years (8 -1 year before final cover)-85%, Final cover 90%

For this study, as far as landfill Gas collection efficiency is concerned scenario 1

"Typical" was considered.

Moisture Condition and Decay Rate

Moisture conditions and associated municipal solid waste bulk decay rate best describe the average conditions at landfills. The rate of change for the decomposition of organic waste in landfills each year (yr-1) is described by the decay rates, commonly known as k values. Waste breaks down more quickly at a landfill when the average decay rate is higher. For this study, wet moisture condition and decay rate-k=0.06 was considered because Abbottabad receive precipitation greater than 40 inches per year.

c. Incineration

Incineration refers to the burning of Municipal solid waste in waste-to-energy (WTE) facilities - A Mass Burn Facility. It produce electricity and steam from the burning of mixed MSW.

d. Recycling

open loop/ closed loop recycling

e. Anaerobic Digestion

In this study, anaerobic digestion refers to wet Anaerobic Digestion (single-stage, wet, mesophilic digester) as food waste contains high moisture content. It was also assumed that the Anaerobic digestion processes would produce digestate, which would then be applied to land. Before being applied to the land, the digestate is cured. Digestate is dewatered after it has been cured. The digestate is subsequently filtered and spread over agricultural fields after being aerobically cured in turned windrows. In addition, the results of biogas will be used for electricity generation.

f. Composting

Here composting refers to central composting facilities with windrow piles and the resultant compost will offset the synthetic fertilizers.

3.3.7 Transport Distance of the Current Waste Treatment / Management Facility

We have estimated that the distance is 8 kilometers on average as the point of collection of waste is assumed to be the same along with assuming that all the waste is then transported from that point of collection to the Salhad dumpsite. The transport distance considered in this study 4.97 miles as the WARM model accept travel distance in miles only and here the distance means distance from curb side to treatment facility.

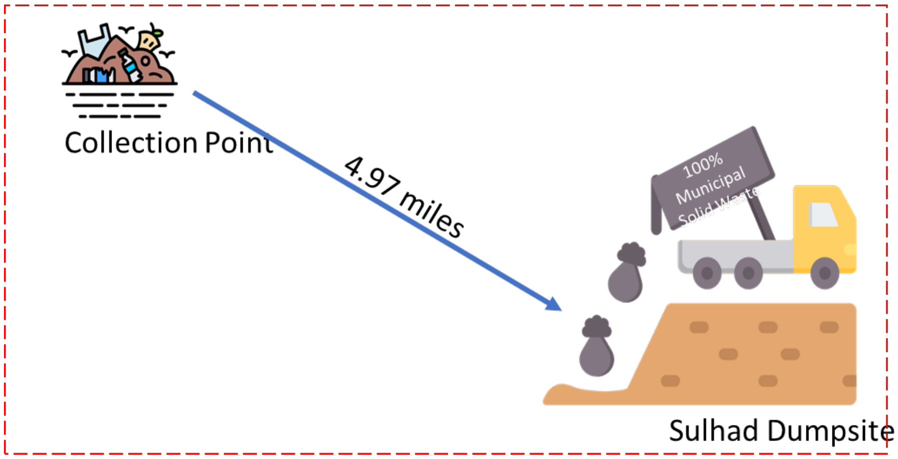

Figure 3.10 Transport Distance

CHAPTER 4: RESULTS AND DISCUSSION

This chapter briefly summarize the results of data analysis, discuss these findings thoroughly and addressed the research objectives and questions of the study by utilizing tables, figures, and relevant references from the literature in a structured and understandable manner. It also provides further direction for future studies.

4.1. Material-Specific Greenhouse Gas Emission and Energy Consumption

This study measures the Greenhouse Gas Emission in Metric Ton of Carbon Dioxide Equivalent and energy consumption in Million British Thermal Units from each component of solid waste specifically paper, plastic, and food waste by treating it with different solid waste management practices which including three variations of Landfill (Landfill without Landfill Gas Recovery System, Landfill with Landfill Gas Control System for energy recovery and open flaring), Incineration, Anaerobic Digestion, composting and recycling.

4.1.1. Mixed Paper (Primarily Residential)

The percentage composition of paper in Abbottabad's municipal solid waste is 12.9%. As WARM accepts value in short tons, the quantity of paper waste per year was calculated to be 11233 short tons/year. In the WARM model, available subcategories of paper waste include magazines/third-class mail corrugated containers, newspapers, phonebook, office paper, textbooks, mixed paper (general), and mixed paper (primarily residential) (US EPA 2016). In this study, we assume the paper belongs to the category of mixed paper (primarily residential). Comparative analysis was conducted by measuring greenhouse gas emissions and energy consumption from treating the same amount of mixed paper (primarily residential) with different municipal solid waste management techniques which include three variations of Landfill (Landfill without Landfill Gas Recovery System, Landfill with Landfill Gas Control System for energy recovery and open flaring), Incineration, Anaerobic Digestion, Composting and recycling (Martins et al. 2023). The results of greenhouse gas emissions are shown in Figure 4.1. and 4.2 shows the results of energy consumption in each municipal solid waste management technique which include three variations of Landfill (Landfill without Landfill Gas Recovery System, Landfill with Landfill Gas Control System for energy recovery, and open flaring), Incineration, Anaerobic Digestion, Composting and recycling.

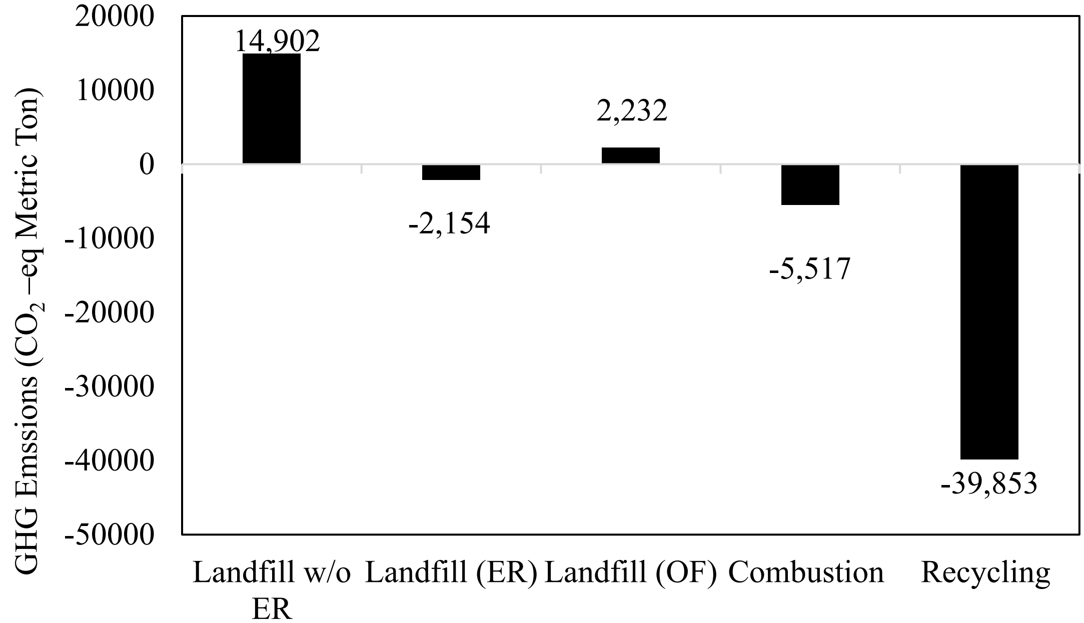

Figure 4.1 GHG Emissions from Treating Paper Waste with Different SWM Techniques

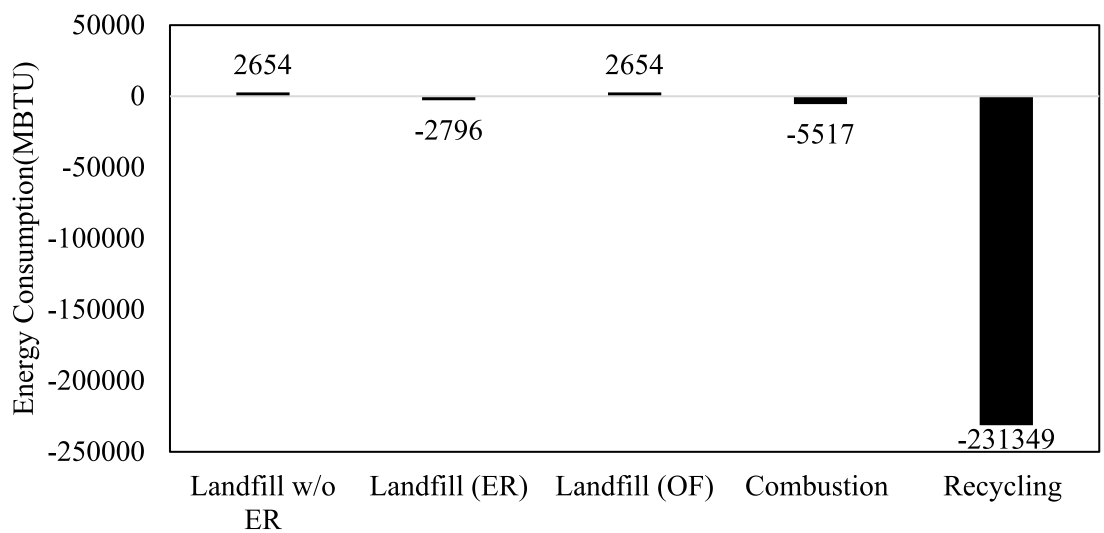

Figure 4.2 Energy Consumptions from Treating Paper Waste with Different SWM Techniques

For paper Recycling found to be the best technology with GHG reduction benefits up to 367% and energy savings of 8816% as compared to GHG emission and energy consumption from simply dumping the paper waste on open ground (Merrild, Damgaard, and Christensen 2009). Paper is modeled as closed-loop recycling in WARM. It means the paper will be recycled again in to paper product (primary products) instead of its transformation in the secondary product (Jauhari et al. 2020). Reduction is because;

- It partially mitigates the "upstream" greenhouse gas emissions caused by the procurement of raw materials, production, and shipping of virgin materials.
- The quantity of carbon stored in forests rises as a result. Materials originating from virgin sources are replaced by recycled materials.

4.1.2. Mixed Plastic

The percentage composition of plastic in Abbottabad's municipal solid waste is 10.3%. As WARM accepts value in short tons, the quantity of plastic waste per year was calculated to be 8960 short tons/year. In the WARM model, available sub categories of plastic waste include, LDPE, HDPE, LLDPE, PET, PS, PP, PVC, and mixed plastics in this study we assume the plastics belong to the category of mixed plastics (U.S. EPA 2016). Comparative analysis was conducted by measuring greenhouse gas emissions and energy consumption from treating the same amount of mixed paper plastics with different municipal solid waste management techniques which include three variations of Landfill (Landfill without Landfill Gas Recovery System, Landfill with Landfill Gas Control System for energy recovery and open flaring), Incineration, Anaerobic Digestion, Composting, and recycling (Liu, Sun, and Liu 2017). Results of greenhouse gas emissions are shown in Figure 4.3 and figure 4.4 shows the results of energy consumption in each municipal solid waste management technique which includes three variations of Landfill (Landfill without Landfill Gas Recovery System, Landfill with Landfill Gas Control System for energy recovery and open flaring), Incineration, Anaerobic Digestion, Composting, and recycling.

For mixed plastic, Recycling was found to be the best technology with GHG reduction benefits up to 5317% and energy savings of 14935% as compared to GHG emission and energy consumptions from simply dumping the plastic waste on open ground (Gabisa, Ratanatamskul, and Gheewala 2023). Mixed plastics are modeled as closed-loop recycling in WARM. It means the plastic will be recycled again in to plastic product (primary product) instead of its transformation in secondary product (Zhao et al. 2022). Reduction is due to the fact that

- It partially mitigates the "upstream" greenhouse gas emissions caused by the procurement of raw materials, production, and shipping of virgin materials.

- The quantity of carbon stored in forests rises as a result. Materials originating from virgin sources are replaced by recycled materials (US EPA 2019).

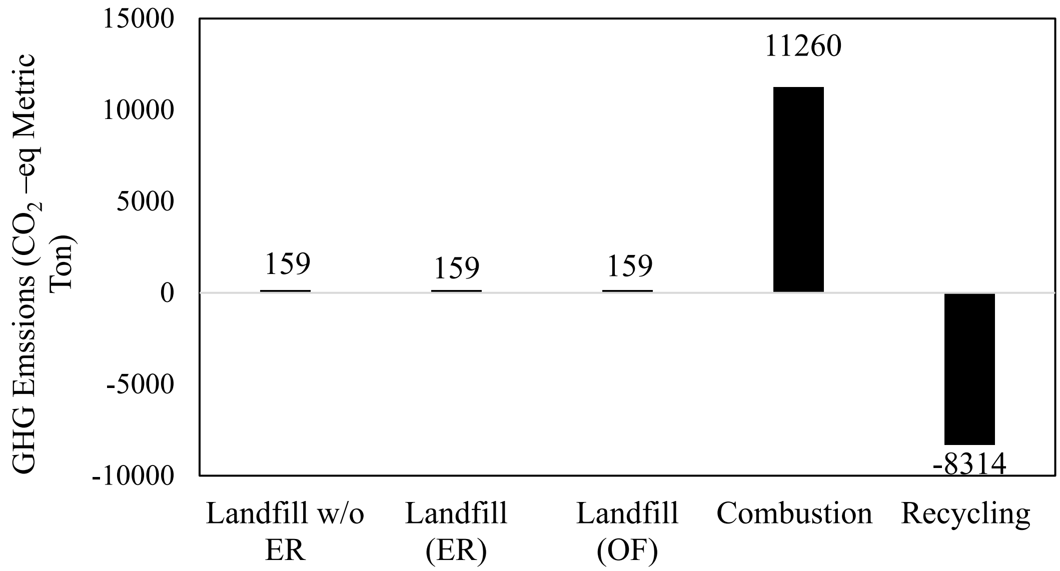

Figure 4.3 GHG Emissions from Treating Plastic Waste with Different SWM Techniques

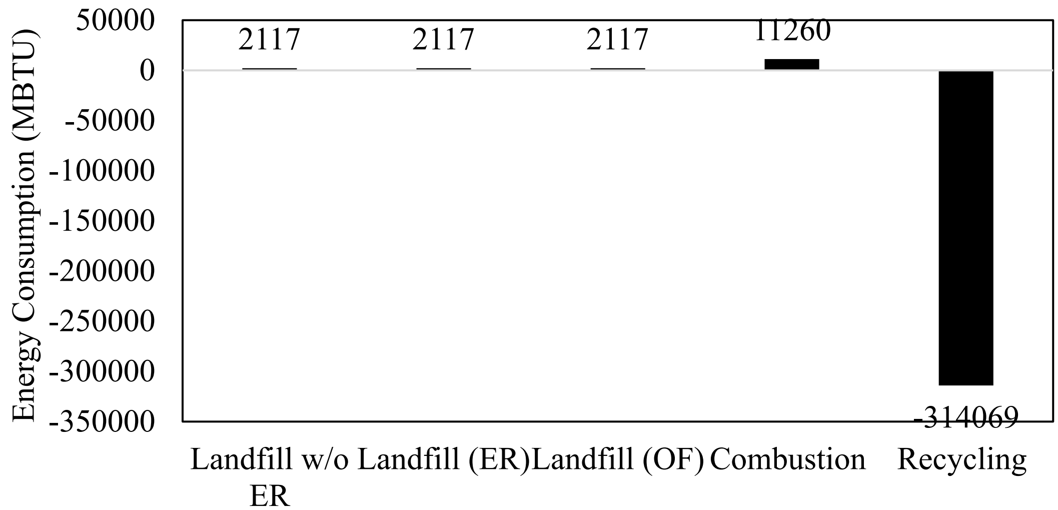

Figure 4.4 Energy Consumptions from Treating Plastic Waste with Different SWM Techniques

4.1.3. Food Waste

The percentage composition of food waste and yard waste in Abbottabad's municipal solid waste is 74.3%. As WARM accepts value in short tons, the quantity of food waste per year was calculated to be 64602 short tons/year. In the WARM model, available subcategories of food waste include food waste, food waste (meat only), food waste (non-meat), beef, grains, poultry, bread, vegetables, fruits and dairy products, and yard waste including yard trimmings, grass, leaves, and branches, in this study we assume the food waste and yard waste belongs to the category of food waste (U.S Environmental Protection 2016). Comparative analysis was conducted by measuring greenhouse gas emissions and energy consumption by treating the same amount of food waste with different municipal solid waste management techniques which include three variations of Landfill (Landfill without Landfill Gas Recovery System, Landfill with Landfill Gas Control System for energy recovery and open flaring), Incineration, Anaerobic Digestion and Composting (Yaman 2020). The results of greenhouse gas emissions are shown in Figure 4.5.

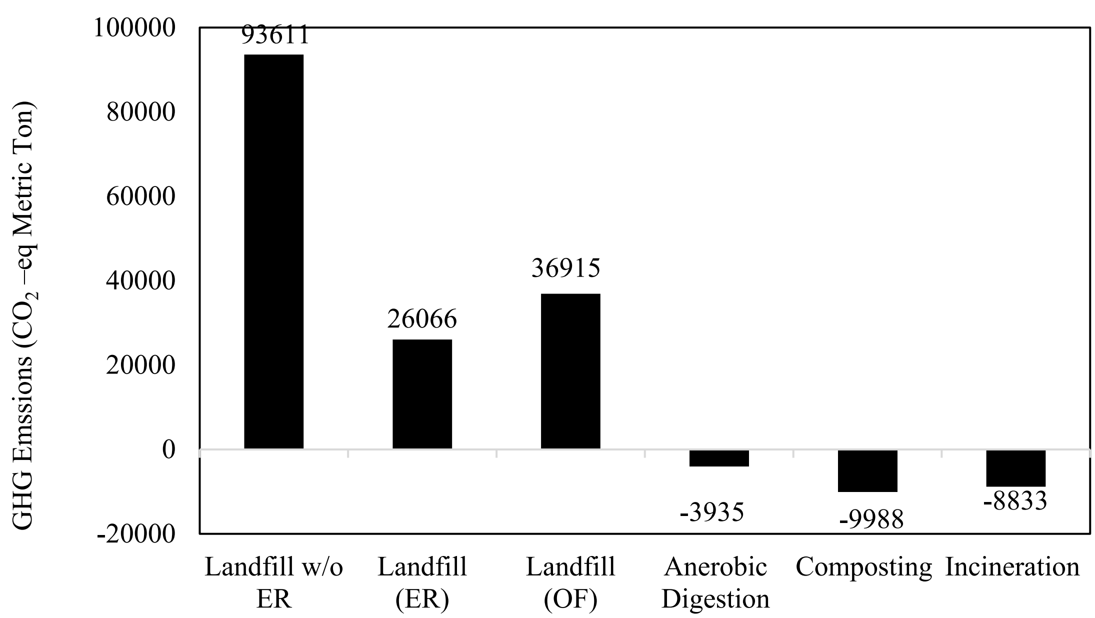

Figure 4.5 GHG Emissions from Treating Food Waste with Different SWM Techniques

For food waste composting found to be the best technology with GHG reduction benefits up to 110% as compared to GHG emissions from simply dumping it on open ground.

Figure 4.6 shows the results of energy consumption in each municipal solid waste management technique which includes three variations of Landfill (Landfill without Landfill Gas Recovery System, Landfill with Landfill Gas Control System for energy recovery and open flaring), Incineration, Anaerobic Digestion and Composting. In this case incineration was found to be the best technology with maximum energy saving of 1058% as compared to baseline solid waste management scenario and composting with net energy consumption 44900 MBTU (Zafar et al. 2024). This is because of the fact that energy will be consumed in incineration as well as produced as food waste is burned in mass burn facility producing energy for electric production (Zafar et al. 2024). Whereas in case in composting energy is consumed to run central composting facility and result compost will offset the synthetic fertilizers. In a nutshell, composting is best because it reduces high amount of GHG gas emission as compared to other technologies (Jeong et al. 2018).

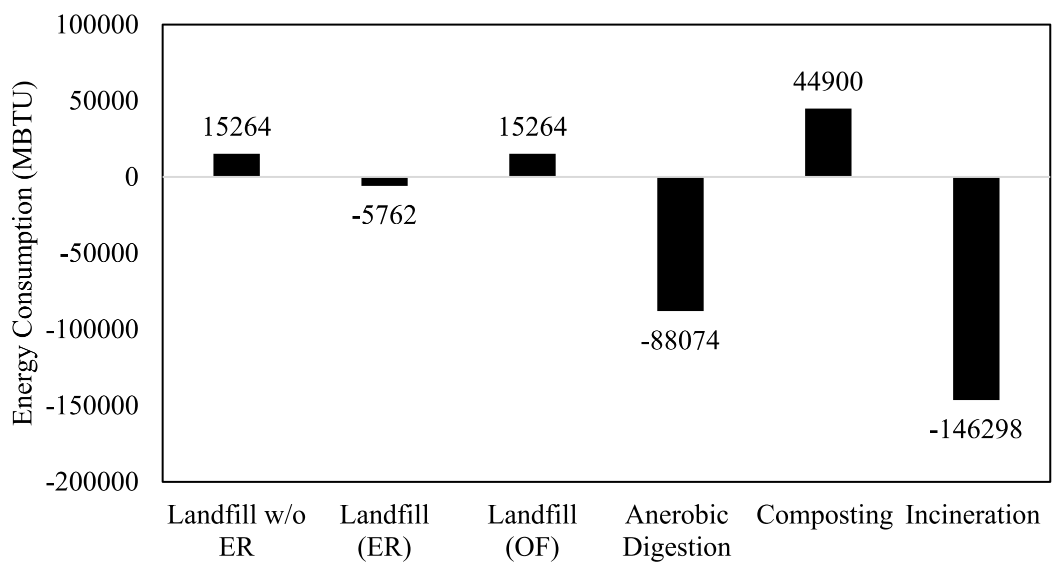

Figure 4.6 Energy Consumption from Treating Food Waste with Different SWM Techniques

4.2. Greenhouse Gas Emission and Energy Consumption from Different Municipal Solid Waste Management Scenarios

This study examined and assessed existing solid waste management practices of Abbottabad city and compared them with the modeled eight municipal solid waste management scenarios to propose a sustainable and environmentally friendly municipal solid waste management strategy based on Greenhouse Gas Emission in Metric Ton of Carbon Dioxide Equivalent and energy consumption in Million British Thermal Unit using excel based, Life Cycle Assessment Tool by US-EPA Waste Reduction model version 16 (US EPA 2016).

4.2.1. Scenario 1- Open Dumping

Scenario 1 was a baseline waste management scenario in which 100% of the Municipal solid waste was open-dumped in a Salhad dumpsite producing total GHG emissions amounting to 0.1 million metric tons of CO_2 equivalents. Results show maximum contribution to total greenhouse gas emissions is food waste 86% because food waste has biodegradable content followed by mixed paper (Bhatia et al. 2023). Total Emission comprise on transportation of municipal solid waste to the dumpsite and landfill emissions due to the biodegradation of organic fraction of the solid waste whereas emissions offset includes landfill carbon storage (Verma and Borongan 2022). Other components of the solid waste contribute very little to the total greenhouse gas emissions as these components are either inert material or inorganic as shown in Figure 4.7

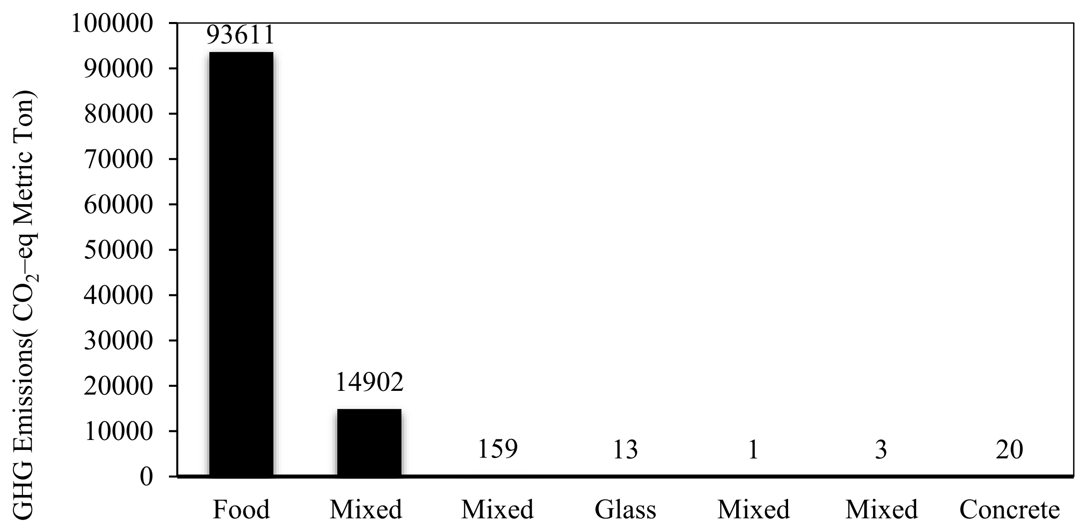

Figure 4.7 GHG Emissions from Scenario 1- Open Dumping

Figure 4.8 shows energy consumption by scenario 1 and the contribution of each component of municipal solid waste to total energy consumption. The total energy consumption is 20534 MBTU in which significant contribution is of food waste, paper and plastic because percentage composition of these solid waste fraction is high as compared to other inorganic and inert component which include glass, metals, electronics and concrete (Alabdraba and AL-Qaraghully 2022). In this scenario, the total energy consumption is due to the transportation of solid waste to the dumpsite located at distance of 8 km from the collection point (Abdel-Shafy and Mansour 2018). A major contribution is of food waste because the quantity of food waste is 64602 short tons 74.3% of the total waste, followed by 11233 short tons of paper and 8960 short tons of plastic waste which is 13% and 10.3% respectively.

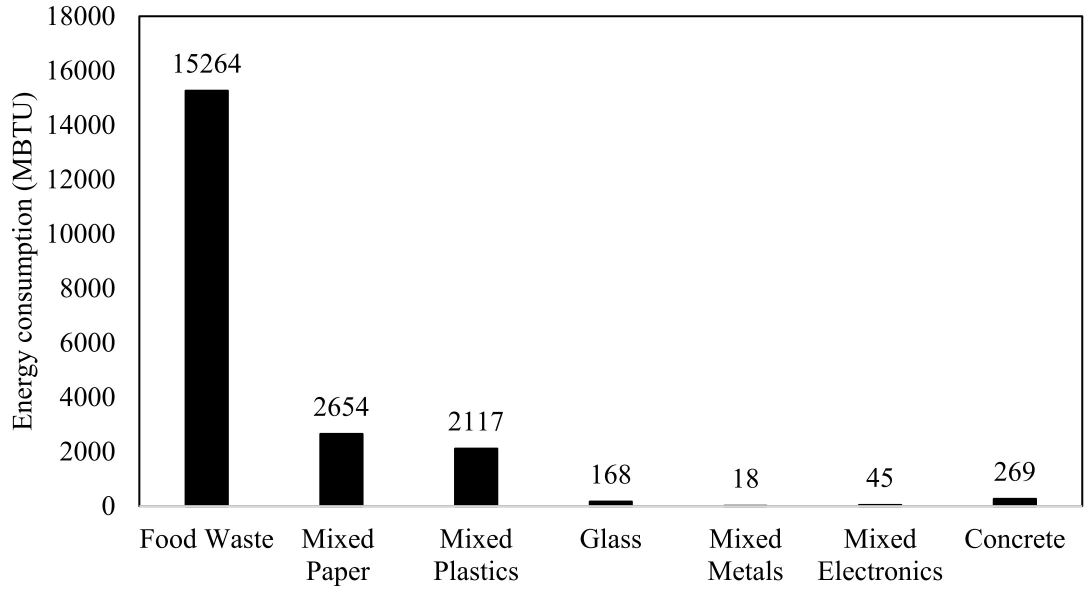

Figure 4.8 Energy Consumption from Scenario 1- Open Dumping

4.2.2. Scenario 2- Landfill with LFG for Energy Recovery

Scenario 2 was a proposed municipal solid waste management scenario in which 100% of the Municipal solid waste was considered to be landfilled producing total GHG emissions amounting to 0.024 million metric tons of CO_2 equivalents. In this scenario, it was assumed that the landfill site has a proper landfill gas control system in which landfill gas would be recovered and used further to generate electricity (Srivastava and Chakma 2020), as previously mentioned in the methodology section. Results shows significant GHG emission reduction up to 78% as compared to the baseline solid waste management scenario. Reduction is due to energy recovery for electricity production (Srivastava and

Chakma 2020). A similar result was also reported by the (Castigliego et al. 2021). Results show maximum contribution to total greenhouse gas emissions is food waste because food waste has biodegradable content. Total Emission comprise on transportation of municipal solid waste to the dumpsites and landfill emissions due to the biodegradation of organic fraction of the solid waste whereas emissions offset include landfill carbon storage that is why paper is showing greenhouse gas reduction benefit of 2154 metric ton of CO_2 equivalents. In life cycle assessment studies, negative sign shows greenhouse gas reduction benefits (Goglio et al. 2020). Other component of the solid waste contribute very less in the total greenhouse gas emission as these components are either inert material or inorganic in nature as shown in Figure 4.9.

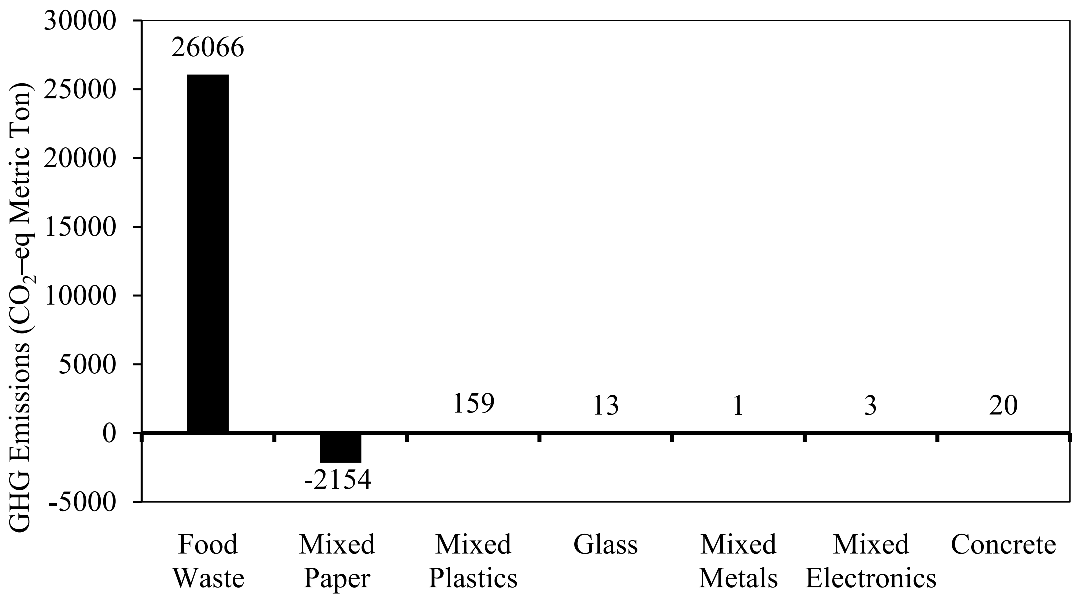

Figure 4.9 GHG Emissions from Scenario 2- Landfill with LFG for Energy Recovery

Figure 4.10 shows energy consumption by scenario 2 and contribution of each component of municipal solid waste in total energy consumption. The total or net energy consumption is -5942 MBTU. In life cycle assessment studies, negative sign shows energy savings (Feo and Malvano 2009). In this scenario, not only energy consumption is reduced but also it results in energy savings up to 129% as compared to baseline solid waste management scenario. In total energy saving, significant contribution is of food waste, paper and plastic because percentage composition of these solid waste fraction is high as compared to other inorganic and inert component which include glass, metals, electronics and concrete because total energy consumption due to transportation of solid waste to the dumpsite located at distance of 8 km from the collection point is greatly offset by the electricity production from the recovered methane or landfill gas (Shovon et al. 2024). In addition, other inert and inorganic component did not contribute in energy saving rather in energy consumption.

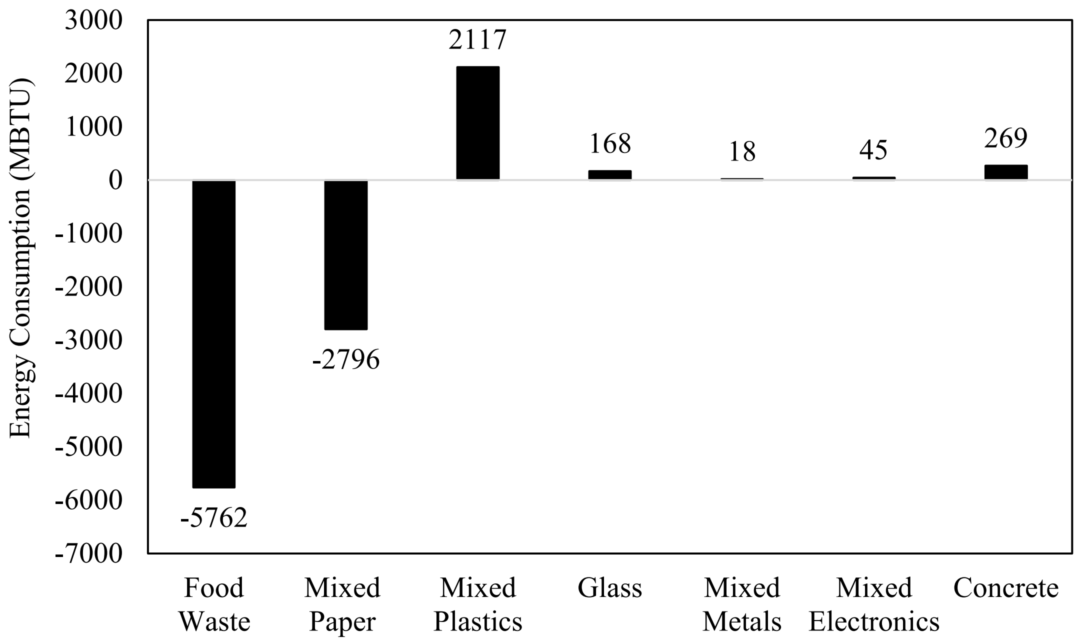

Figure 4.10 Energy Consumption from Scenario 2- Landfill with LFG for Energy Recovery

4.2.3. Scenario 3- Landfill with LFG for Open Flaring

Scenario 3 was a proposed municipal solid waste management scenario in which 100% of the Municipal solid waste was considered to be landfilled producing total GHG emissions amounting to 0.039 million metric tons of CO_2 equivalents. In this scenario, it was assumed that the landfill site is having a proper landfill gas control system in which landfill gas would be recovered for open flaring as previously mentioned in the methodology section. Results shows significant GHG emission reduction up to 63% as compared to the baseline solid waste management scenario. A similar result was also reported by the (Castigliego et al. 2021). Results show maximum contribution to total greenhouse gas emissions is food waste because food waste has biodegradable content. Total Emission comprises on transportation of municipal solid waste to the dumpsite and landfill emissions due to the biodegradation of organic fraction of the solid waste whereas emissions offset includes landfill carbon storage. Other component of the solid waste contribute very less in the total greenhouse gas emission as these components are either inert material or inorganic in nature as shown in the Figure 4.11.

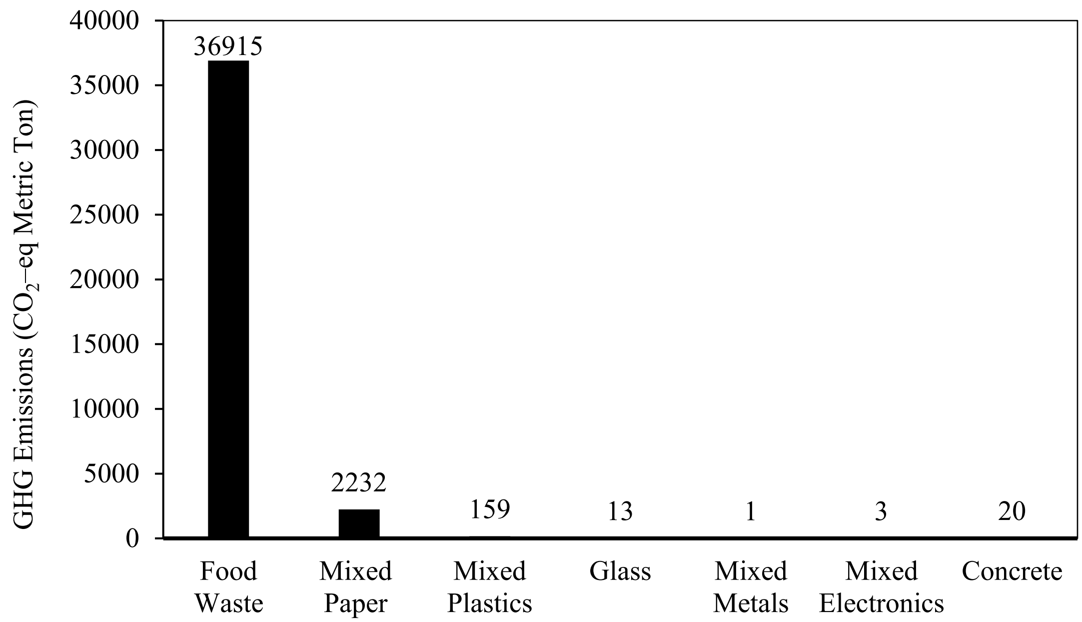

Figure 4.11 GHG Emissions from Scenario 3- Landfill with LFG for Open Flaring

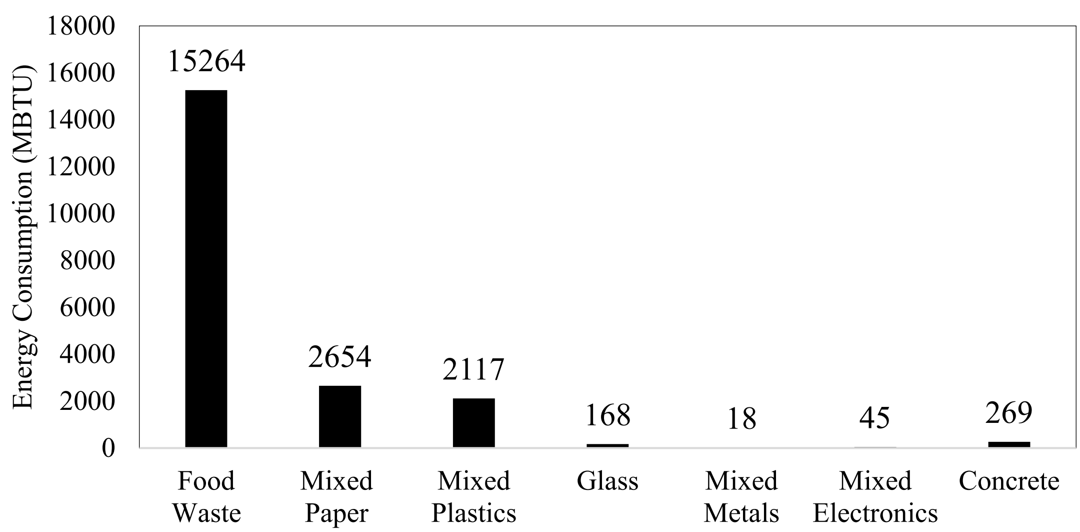

Figure 4.12 Energy Consumptions from Scenario 3- Landfill with LFG for Open Flaring

Figure 4.12 shows energy consumption by scenario 3 and contribution of each component of municipal solid waste in total energy consumption. The total energy consumption is 20534 MBTU in which significant contribution is of food waste, paper and plastic because percentage composition of these solid waste fraction is high as compared to other inorganic and inert component which include glass, metals, electronics and concrete. In this scenario the total energy consumption is due to transportation of solid waste to the dumpsite located at distance of 8 km from the collection point. Major contribution is of food waste because the quantity of food waste is 64602 short ton 74.3% of the total waste, followed by 11233 short ton of paper and 8960 short ton of plastic waste which is 13% and 10.3% respectively.

4.2.4. Scenario 4- Anaerobic Digestion for Food Waste

In previous scenarios, it was found that the major contribution to the total greenhouse gas emissions is due to the high percentage composition of organic waste which mainly comprise on food waste that is 74.3%. It indicates that proper solid waste management for the treatment of organic waste is critical to reduce the total greenhouse gas emissions.

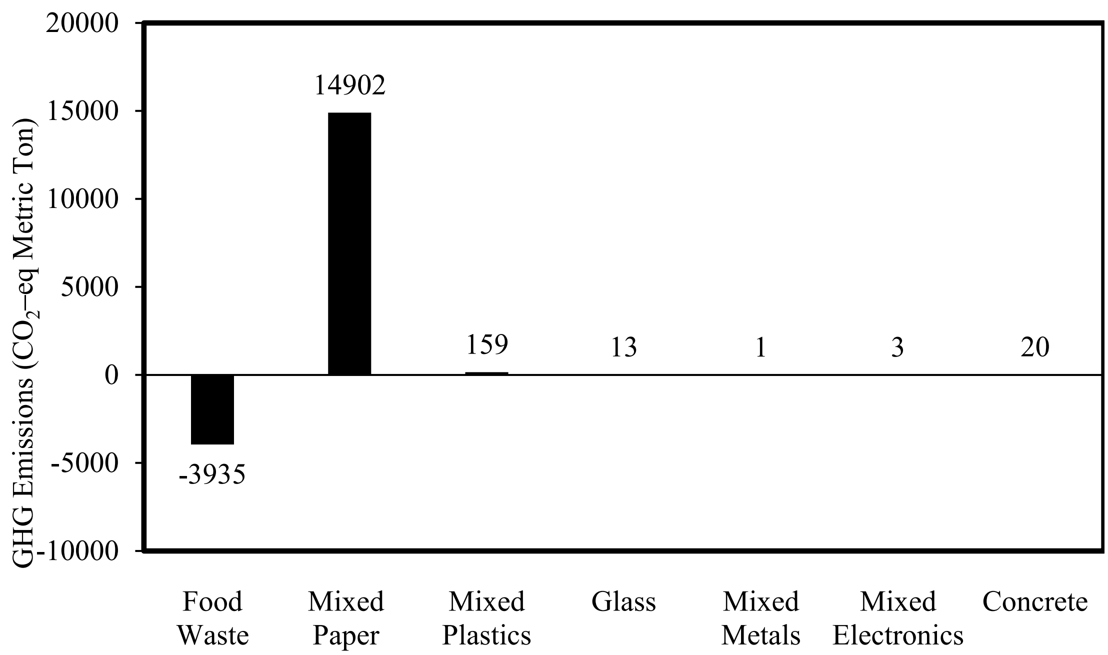

Figure 4.13 GHG Emissions from Scenario 4- Anaerobic Digestion and Landfill without LFG

Considering the situation, scenario 4 was proposed as a municipal solid waste management scenario in which only food waste (74.3% of the total waste) was considered to be anaerobically digested in the wet anaerobic single-stage, mesophilic digester and the rest of the solid waste was considered to be landfill without landfill gas recovery system for energy recovery or open flaring (Burmistrova et al. 2022). In addition, it was considered that resultant biogas would be used for electricity generation and resultant digestate would be cured aerobically in a turned windrow (Morgan et al. 2001) and then it would be applied to the agricultural fields as previously mentioned in the methodology section.

This scenario is producing total GHG emission amounting 0.011 million metric ton of CO_2 equivalents. Results shows significant GHG emission reduction up to 89% as compared to baseline solid waste management scenario. Reduction is due to biogas recovery for electricity production and land application of digestate from the AD of food waste. Food waste cause greenhouse gas reduction benefit of 3935 metric tons of CO_2 equivalents. In life cycle assessment studies, a negative sign shows greenhouse gas reduction benefits (Goglio et al. 2020). Results shows maximum contribution in total greenhouse gas emission is of paper waste and minor contribution of other inorganic and inert material as shown in Figure 4.13.

Figure 4.14 shows energy consumption by scenario 4 and the contribution of each component of municipal solid waste to total energy consumption. The total or net energy consumption is -82804 MBTU. In life cycle assessment studies, a negative sign shows energy savings (Goglio et al. 2020). In this scenario, not only energy consumption is reduced but also it results in energy savings up to 503% as compared to baseline solid waste management scenario. In total energy saving, a significant contribution is of food waste that is -88074 MBTU, because the percentage composition of food waste is high as compared to other inorganic and inert component of the total solid waste which include glass, metals, electronics and concrete (Al-Rumaihi et al. 2020). The total energy consumption due to the transportation of solid waste to the dumpsite located at a distance of 8 km from the collection point is greatly offset by the biogas collection for electricity production and land application of digestate instead of synthetic fertilizer (Abdel-Shafy and Mansour 2018). In addition, other inert and inorganic component did not contribute in energy saving rather in energy consumption. Net energy and emission sources and offsets comprise on;

- transportation of material

- preprocessing of waste and digestor operations
- biogas collection and utilization
- curing of digestate and land application
- fugitive emissions of methane CH_4 and N_2O
- carbon storage after land application
- avoided fertilizer offsets
- net electricity offsets (adjustable for regional electricity grid)

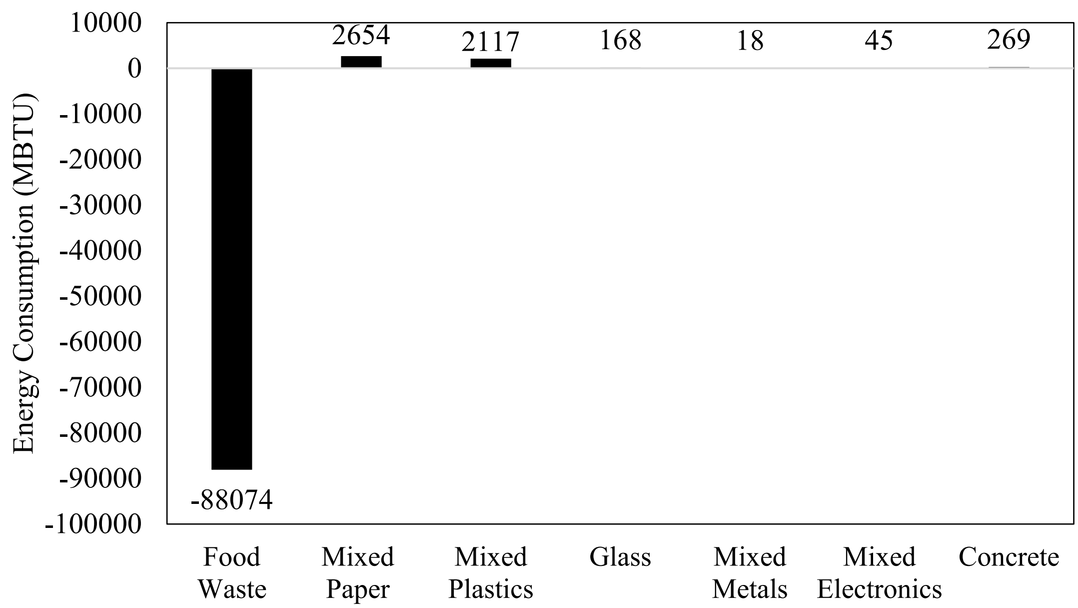

Figure 4.14 Energy consumptions from Scenario 4- Anaerobic Digestion and Landfill without LFG

4.2.5. Scenario 5- Composting for Food Waste

In previous scenarios, it was found that the major contribution in the total greenhouse gas emissions is due to the high percentage composition of organic waste which mainly comprise on food waste that is 74.3%. It indicates that proper solid waste management for the treatment of organic waste is critical to reduce the total greenhouse gas emissions. Considering the situation, the scenario 5 was proposed as municipal solid waste management scenario in which only food waste (74.3% of the total waste) was considered to be Composted in central composting facilities, and rest of the solid waste was considered to be landfill without landfill gas recovery system for energy recovery or open flaring. In addition, it was considered that resultant compost would be used as organic fertilizer in the agricultural fields as previously mentioned in the methodology section. This scenario is producing total GHG emission amounting 5111 metric ton of CO_2 equivalents. Results shows significant GHG emission reduction up to 95% as compared to baseline solid waste management scenario. Reduction is due to land application of resultant compost from the composting of food waste. Food waste cause greenhouse gas reduction benefit of 9988 metric ton of CO_2 equivalents. In life cycle assessment studies, negative sign shows greenhouse gas reduction benefits. Results shows maximum contribution in total greenhouse gas emission is of paper waste which is 14902 metric ton of CO_2 equivalents and minor contribution of other inorganic and inert material as shown in Figure 4.15.

Figure 4.15 GHG Emissions from Scenario 5 – Composting and Landfill without LFG

Figure 4.16 shows energy consumption by scenario 5 and contribution of each component of municipal solid waste in total energy consumption. The total or net energy consumption is 50170 MBTU. In this scenario, energy consumption is get increased up to 144% as compared to the baseline solid waste management scenario. Energy consumption get increased due to the transportation of huge amount of food waste to the composting facility and running the equipment for composting. In addition, no energy is recovered in the form of landfill gas or biogas like in the previous scenarios.

In this scenario energy and emissions sources include;

- transportation of solid waste to the composting facility and landfill facility
- equipment uses
- fugitive emissions of methane CH_4 and N_2O

Emission offsets include carbon storage after land application of compost as an avoided product.

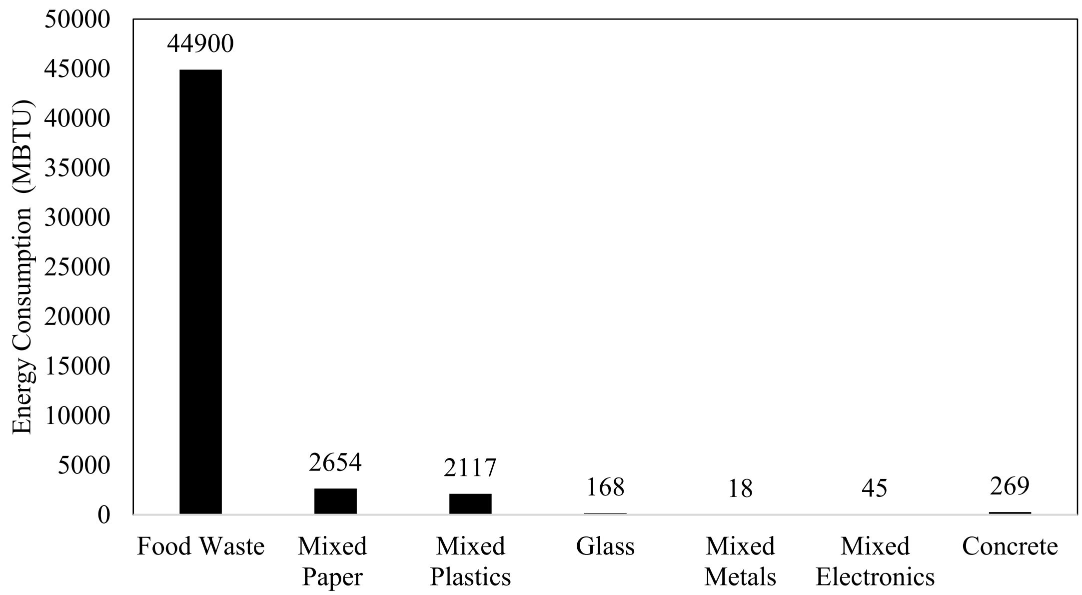

Figure 4.16 Energy Consumptions from Scenario 5 – Composting and Landfill without LFG

4.2.6. Scenario 6- Incineration for Food Waste

In previous scenarios, it was found that the major contribution to the total greenhouse gas emissions is due to the high percentage composition of organic waste which mainly comprises on food waste that is 74.3%. It indicates that proper solid waste management for the treatment of organic waste is critical to reduce the total greenhouse gas emissions. Considering the situation, the scenario 6 was proposed as municipal solid waste management scenario in which only food waste (74.3% of the total waste) was considered to be incinerated in incineration – a mass burn facility and rest of solid waste was considered to be landfill without landfill gas recovery system for energy recovery or open flaring. In addition, it was considered that incinerator will generate electricity/ steam as previously mentioned in the methodology section. It produced total GHG emission amounting 6266 metric ton of CO_2 equivalent. Results shows significant GHG emission reduction up to 94% as compared to baseline scenario. Reduction is due to generation of electricity and offsetting fossil fuel for electricity production from incineration of food waste (Nascimento, Kuramochi, and Moisio 2021). Food waste cause greenhouse gas reduction benefit of 8833 metric ton of CO_2 equivalents. In life cycle assessment studies, negative sign shows greenhouse gas reduction benefits. Moreover, results show maximum contribution in total greenhouse gas emission is of paper waste which is 14902 metric ton of CO_2 equivalents and minor contribution of other inorganic and inert material as shown in Figure 4.17.

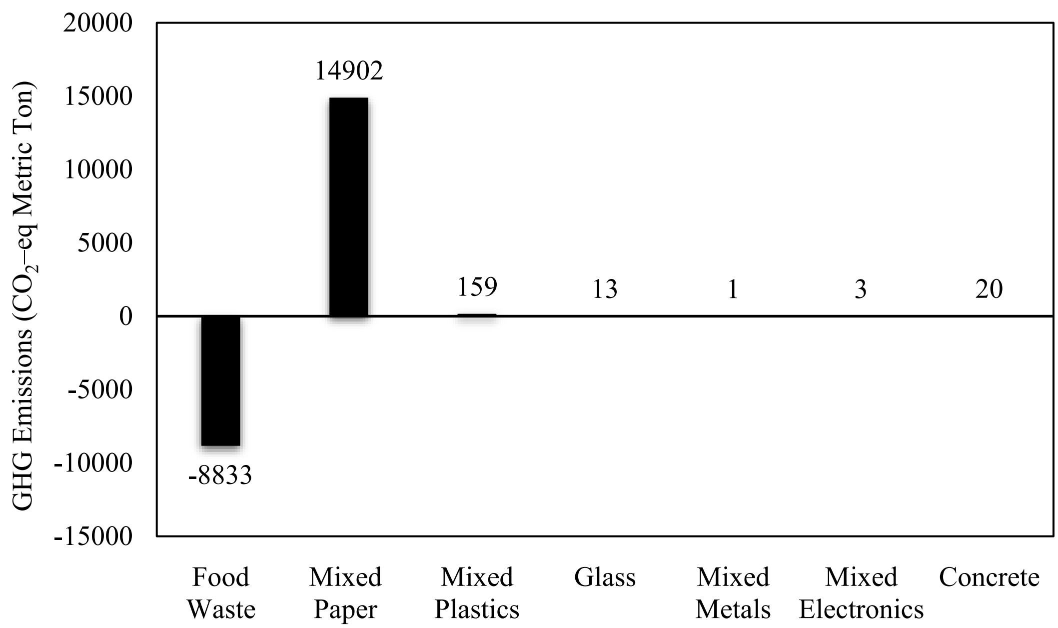

Figure 4.17 GHG Emissions from Scenario 6 – Incineration (Food waste) and Landfill without LFG

Figure 4.18 shows energy consumption by scenario 6 and the contribution of each component of municipal solid waste in total energy consumption. The total or net energy consumption is -141028 MBTU. In life cycle assessment studies, a negative sign shows energy savings. In this scenario, not only energy consumption is reduced but also it results in energy savings up to 787% as compared to baseline solid waste management scenario. In total energy saving, a significant contribution is of food waste that is -146298 MBTU, because percentage composition of food waste is high as compared to other inorganic and inert component of the total solid waste which include glass, metals, electronics and concrete. The total energy consumption due to transportation of solid waste to the dumpsite located at distance of 8 km from the collection point is greatly offset by the steam or electricity generation. In addition, other inert and inorganic component did not contribute in energy saving rather in energy consumption due to its transportation towards dumpsite.

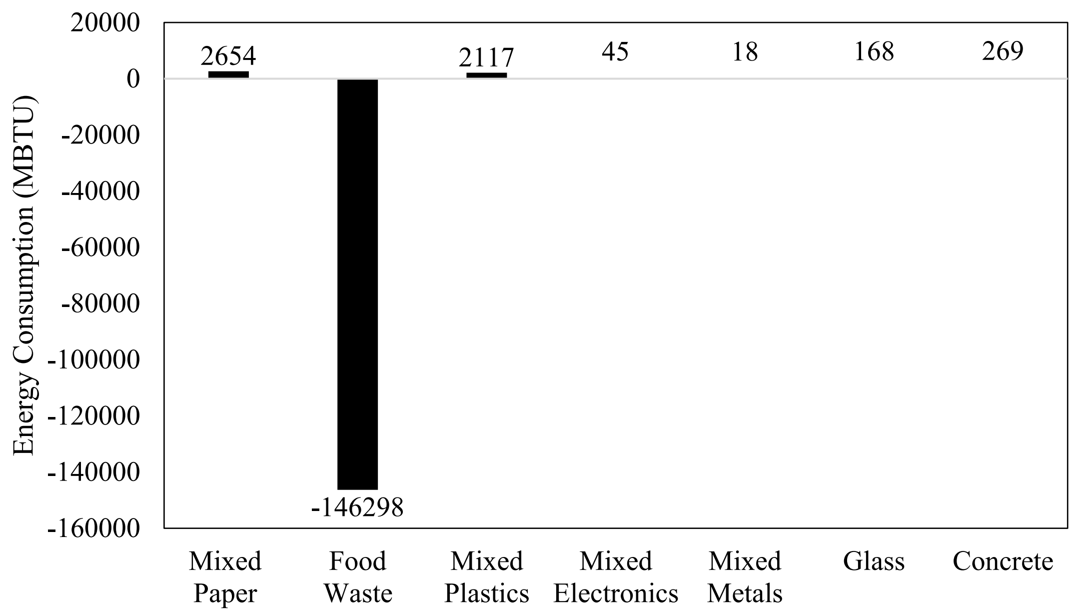

Figure 4.18 Energy Consumptions from Scenario 6 – Incineration (Food waste) and Landfill without LFG

4.2.7. Scenario 7- Incineration for Combustible Materials (Paper and Plastics)

Scenario 7 is a proposed solid waste management scenario in which combustible materials paper and plastic (23.2% of the total municipal solid waste) were sent to incinerators and the rest of the waste (76.8% of the total municipal solid waste) was landfill without any landfill gas recovery system. It produced total GHG emission amounting 0.09 million metric ton of CO_2 equivalent which shows negligible GHG emission reduction that is merely 8% as compared to baseline scenario. Reduction is due to energy production form incinerators to generate electricity that would offset the burning of fossils to generate electricity. Paper requires less amount of fuel to burn as compared to plastic and generate more heat energy than as compared to consumption of energy (Vuppaladadiyam et al. 2024). This minor reduction is due to the fact the percentage composition of paper and plastic which is considered to be incinerated is very less that is 13% an 10.3% respectively. Whereas highest fraction is of food waste 74.3% which is considered to be landfill along with other inert and inorganic materials which include glass, electronics, metal, and concrete. A huge amount of GHG emissions (93611 metric tons of CO_2 equivalent) is due to the transportation of food waste to the dumpsite from the collection point as shown in Figure 4.19.

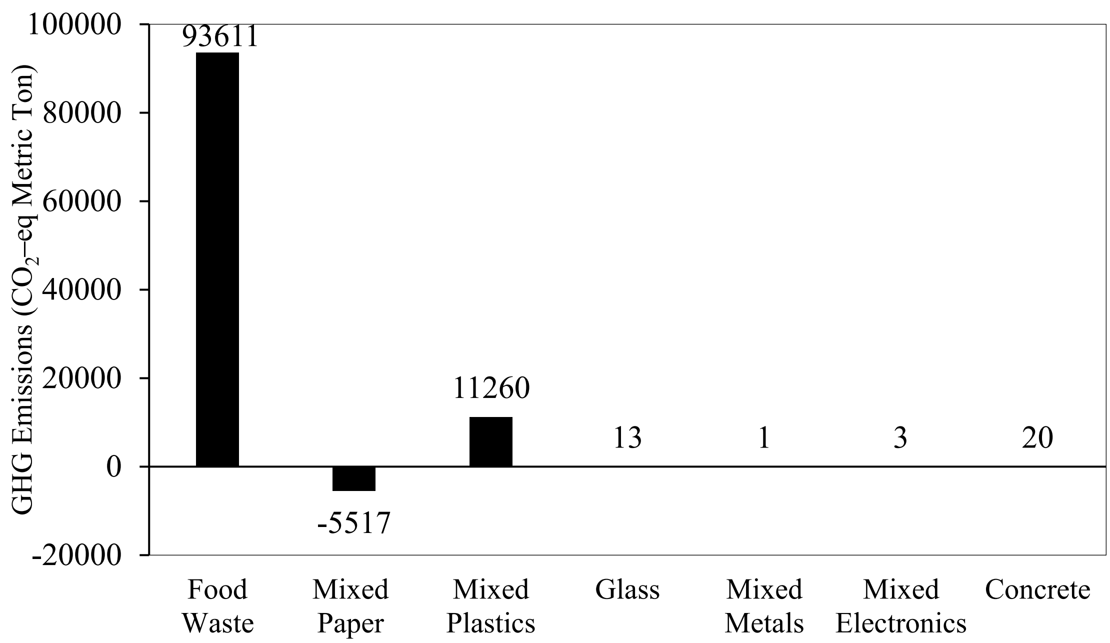

Figure 4.19 GHG Emissions from Scenario 7 – Incineration (Paper and Plastic waste) and Landfill without LFG

Figure 4.20 shows energy consumption by scenario 7 and the contribution of each component of municipal solid waste in total energy consumption.The total or net energy consumption is -180315 MBTU. In life cycle assessment studies, negative sign shows energy savings (Goglio et al. 2020) . In this scenario, not only energy consumption is reduced but also it results in energy savings up to 978% as compared to baseline solid waste management scenario. In total energy saving, significant contribution is of burning of paper and plastic waste that is -74843 MBTU and -121234 MBTU, because of their potential to generate huge amount of energy from burning as compared to other inorganic and inert component of the total solid waste which include glass, metals, electronics and concrete. The resultant energy production would offset the total energy consumption due to transportation of solid waste to the dumpsite located at distance of 8 km from the collection point.

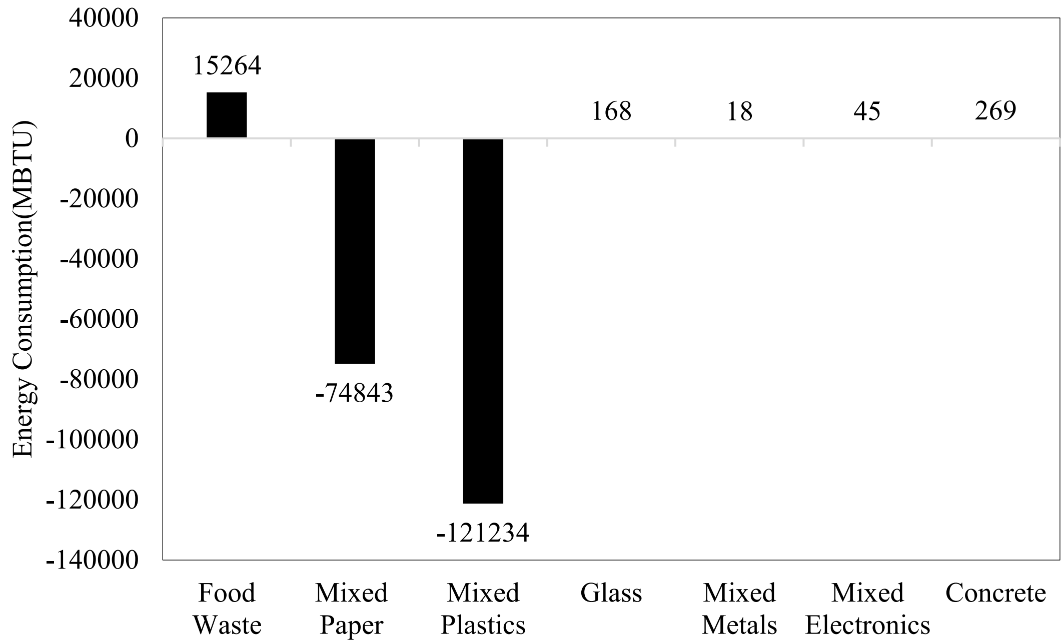

Figure 4.20 Energy Consumptions from Scenario 7 – Incineration (Paper and Plastic waste) and Landfill without LFG

4.2.8. Scenario 8- Recycling for Recyclables

Scenario 8 is a proposed solid waste management scenario in which recyclable materials paper, plastic, glass, metal, electronics, and concrete (25.7% of the total municipal solid waste) were sent to open and closed-loop recycling, and the rest of the food waste (74.3% of the total municipal solid waste) was landfill without any landfill gas recovery system. In the WARM model, materials such as concrete and mixed electronics are represented using open-loop recycling processes. In contrast, glass, paper, plastic, and metal are modeled using closed-loop recycling processes. The decision to categorize materials as open-loop or closed-loop is based on the typical recycling method used for each material. It was found that this scenario produced total GHG emissions amounting to 0.044 million metric tons of CO_2 equivalent which shows a significant GHG emission reduction that is 59% as compared to the baseline scenario. GHG emission reduction is due to the following fact depending on the material being recycled.

- It partially mitigates the "upstream" greenhouse gas emissions caused by the procurement of raw materials, production, and shipping of virgin materials (U.S Environmental Protection 2016), and
- The quantity of carbon stored in forests rises as a result. Materials originating from virgin sources are replaced by recycled materials.

Whereas highest fraction is of food waste 74.3% which is considered to be landfill producing huge amount of GHG emissions (93611 metric ton of CO_2 equivalent) is due to the the transportation of food waste to the dumpsite from the collection point as shown in Figure 4.21.

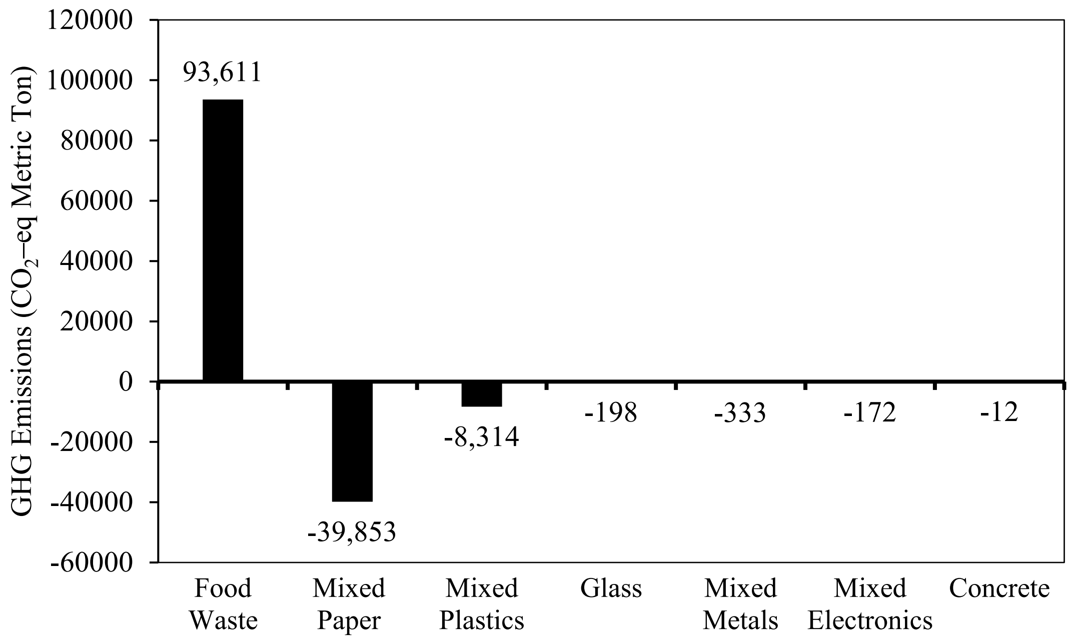

Figure 4.21 GHG Emissions from Scenario 8 – Recycling (Recyclable) and Landfill without LFG (Food waste)

Figure 4.22 shows energy consumption by scenario 8 and the contribution of each component of municipal solid waste to total energy consumption. The total or net energy consumption is -539551 MBTU. In life cycle assessment studies, a negative sign shows energy savings. In this scenario, not only energy consumption is reduced but also it results in energy savings up to 2787% as compared to baseline solid waste management scenario. In total energy saving, a significant contribution is of recycling of paper and plastic waste that is -231349 MBTU and -314069 MBTU, because of their highest recycling potential and highest percentage composition in the total solid waste as compared to other inorganic and inert component of the total solid waste which includes glass, metals, electronics and concrete.

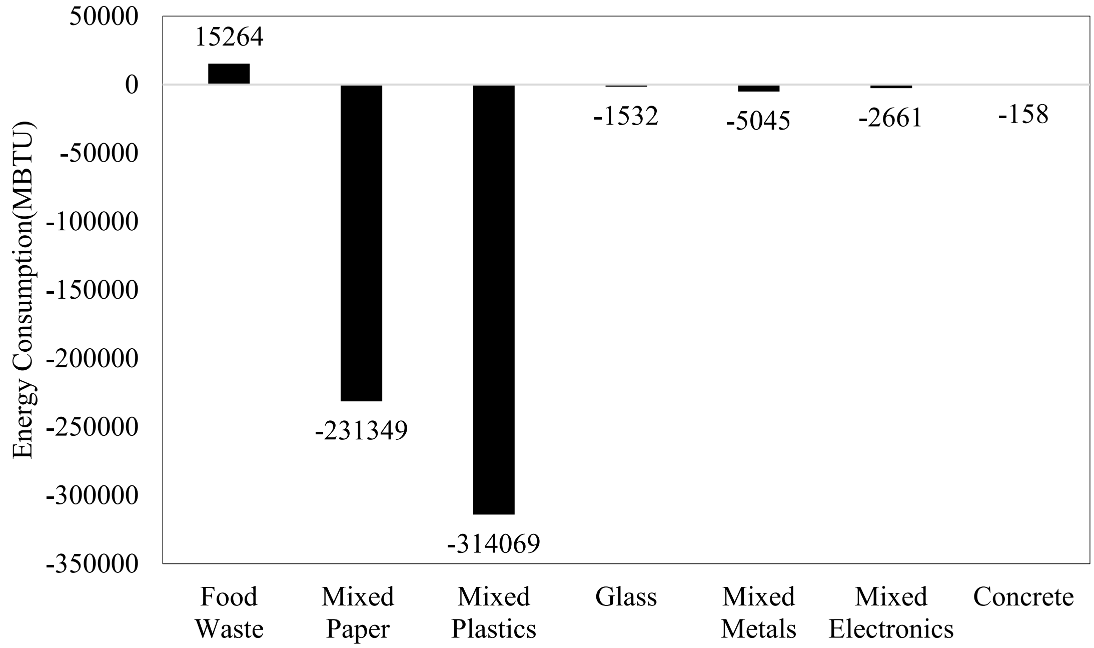

Figure 4.22 Energy Consumptions from Scenario 8 – Recycling (Recyclable) and Landfill without LFG (Food waste)

4.2.9. Scenario 9- Integrated Solid Waste Management

While measuring GHG emissions and energy consumption from all the waste management scenarios it was found that for organic fraction of waste, composting would generate least amount of GHG emissions as compared to other treatment technology which include incineration and anerobic digestion. Whereas for other inorganic and inert fractions of waste recycling was found to be the best treatment technology. Given the above-mentioned discussion of the results, an integrated solid waste management scenario was proposed for the district of Abbottabad. In this scenario, 74.3% of total municipal solid waste, comprising mainly of food waste (organic fraction) was considered to be composted and the rest of the 25.7% of total municipal solid waste, comprising mainly of recyclable (inorganic and inert materials), comprising mainly on paper, plastic, glass, metal, electronics, and concrete was considered to be recycled. In the WARM model, concrete and mixed electronics are treated using open-loop recycling processes, whereas glass, paper, plastic, and metal are managed through closed-loop recycling processes. The choice between open-loop and closed-loop modeling is determined by the most common recycling method for each material. It was found that if both of the treatment technology, recycling and composting is exercised together in solid waste management strategy, GHG emission would be reduced up to 154%. Similar results are also reported by (Mathlouthi et al. 2024).

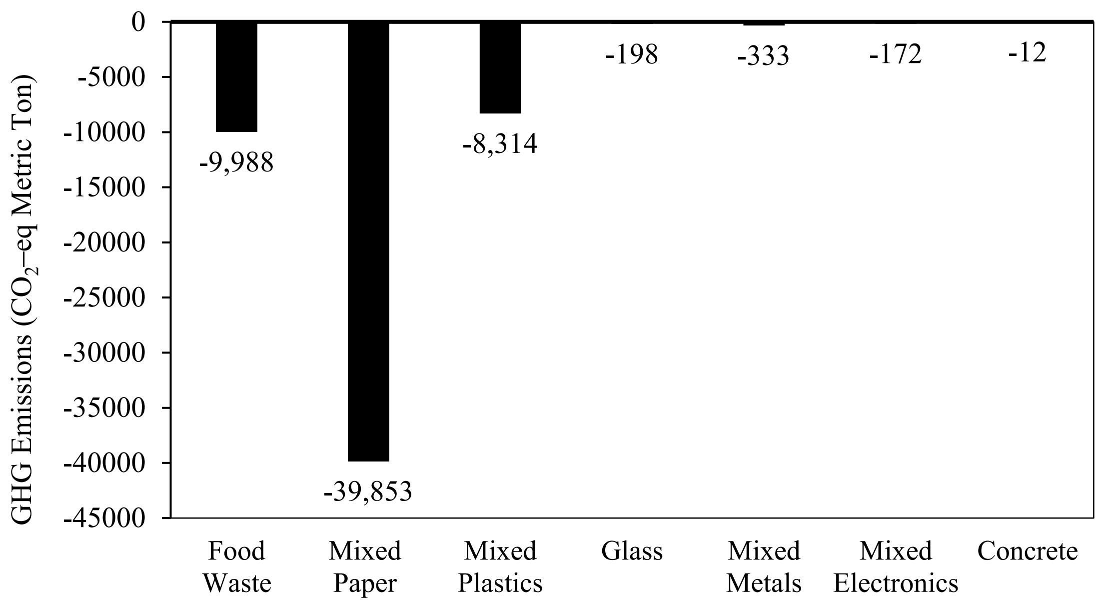

Figure 4.23 GHG Emissions from Scenario 9 – Integrated Solid Waste Management Scenario

Figure 4.24 shows energy consumption by scenario 9 and contribution of each component of municipal solid waste in total energy consumption. The total or net energy consumption is -509914 MBTU. In life cycle assessment studies, negative sign shows energy savings. In this scenario, not only energy consumption is reduced but also it results in energy savings up to 2727% as compared to baseline solid waste management scenario. In total energy saving, significant contribution is of recycling of paper and plastic waste that is -231349 MBTU and -314069 MBTU, because of their highest recycling potential and highest percentage composition in the total solid waste as compared to other inorganic and inert component of the total solid waste which include glass, metals, electronics and concrete. Whereas composting consume energy which is then compensated by energy offsets due to displacement of virgin- sourced material.

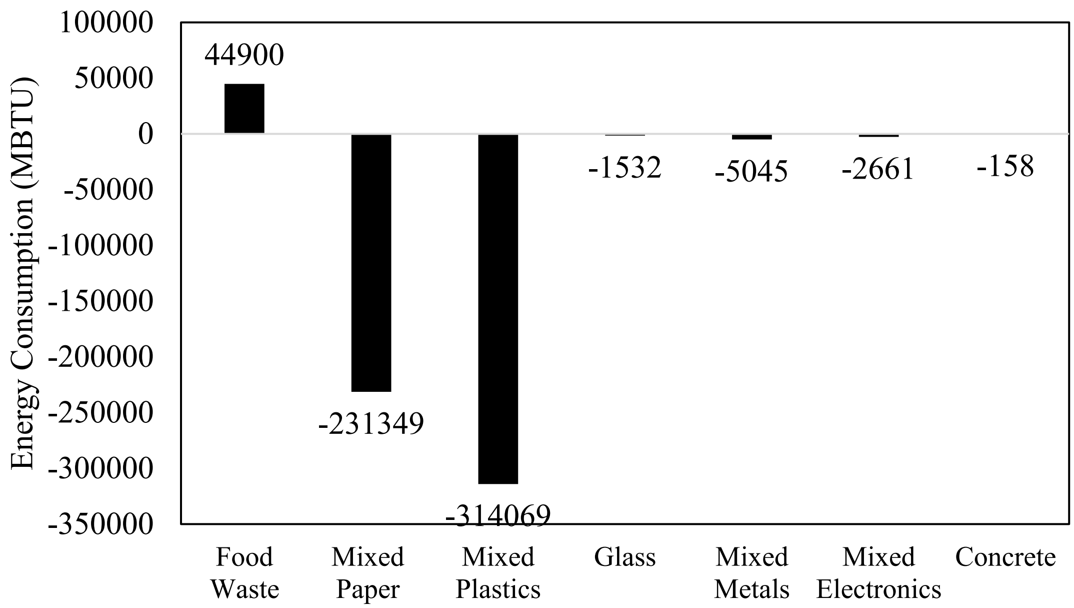

Figure 4.24 Energy Consumptions from Scenario 9 – Integrated Solid Waste Management Scenario

4.3. Comparative Analysis of Modelled Solid Waste Management Scenarios

Figure 4.25 shows the comparative analysis of GHG emissions from all solid waste management scenarios. In previous sections of this chapter, GHG emissions from each solid waste management scenario have been discussed comprehensively.

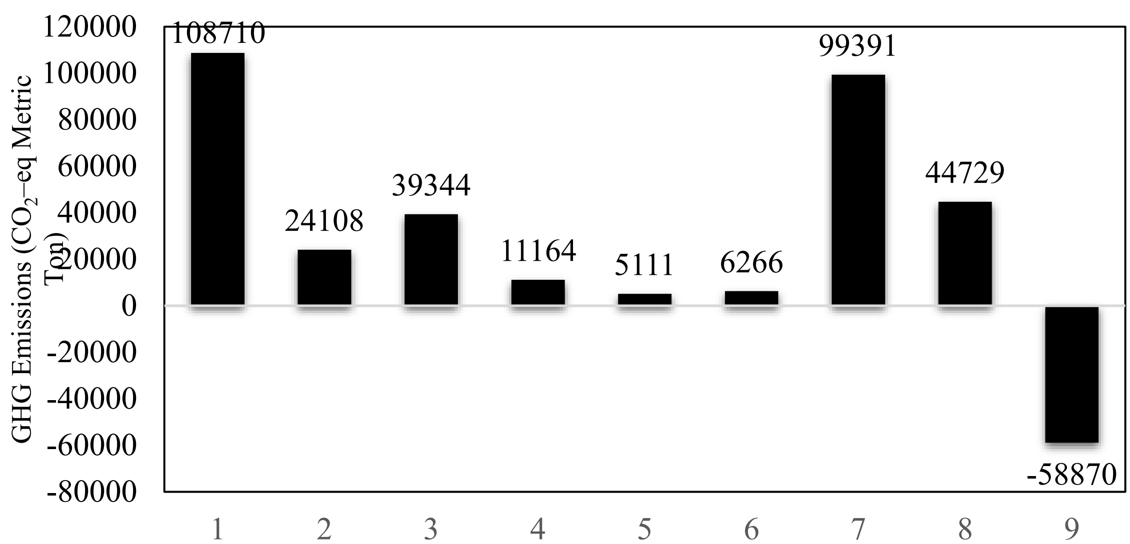

Figure 4.25 Comparative Analysis of GHG Emissions from all Solid Waste Management Scenarios

It is clearly evident that, the integrated solid waste management scenario (scenario – 9) is not only emitting least amount of greenhouse gas but also providing a greenhouse reduction benefit of 58870 metric tons of CO_2 equivalent while comparing it with other solid waste management scenarios. This will reduce GHG emissions by up to 154% as compared to baseline solid waste management- open dumping.

Figure 4.26 shows the comparative analysis of net energy consumption in MBTU from all solid waste management scenarios. In previous sections of this chapter, net energy consumption from each solid waste management scenario has been discussed comprehensively. It is clearly evident that scenario 8 and 9 is causing saving of 2787% and 2727% respectively. So in terms of energy consumption, scenario 8 seems best with highest energy saving of 539551 MBTU but the GHG emissions from scenario 8 is far high than scenario 9, which results in overall GHG benefits. In this way we can say that scenario 9 is best solid waste management scenario for district Abbottabad.

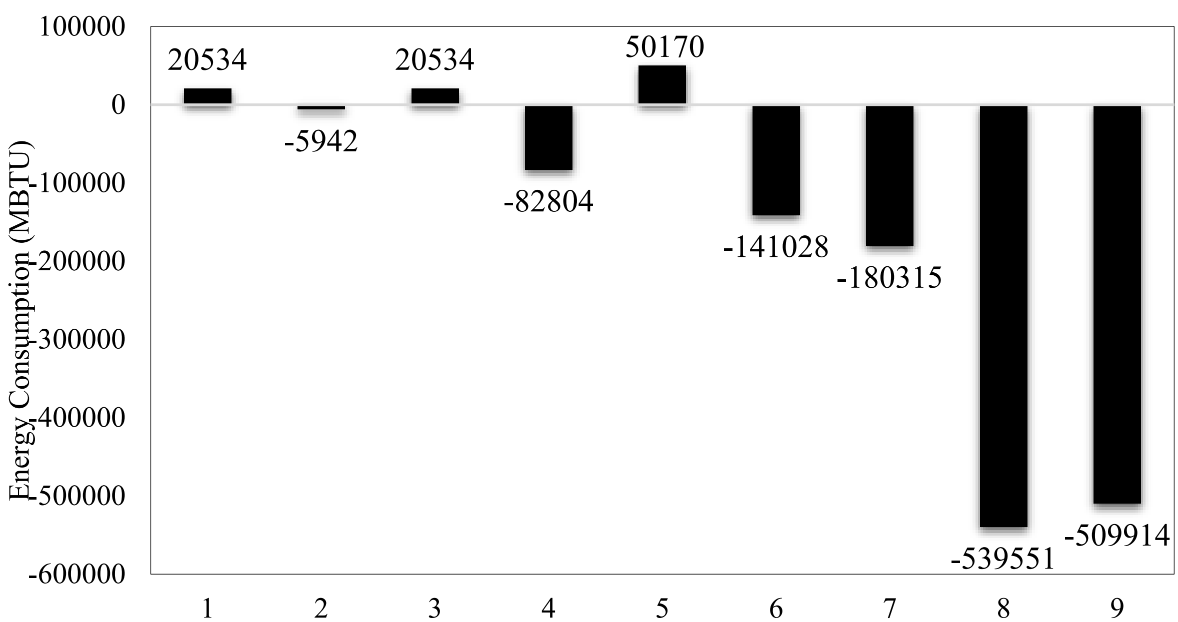

Figure 4.26 Comparative Analysis of Energy Consumption from all Solid Waste Management Scenarios

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the conclusion drawn from the result and discussion chapter of this study is presented along with actionable recommendation as step 4 of life cycle assessment- Interpretation of Results. This study successfully addresses the research goal and objectives defined in chapter 1 using the methodology of Life Cycle Assessment and LCA Tool created by US- EPA -Waste Reduction Model version 16.

5.1. Conclusions

The existing solid waste management practice in district Abbottabad is open dumping of solid waste in the salhad dumpsite located of district Abbottabad at the entrance of city, polluting nearby salhad stream through leachate contamination. It is due to that fact that existing solid waste management system is facing numerous challenges which include improper solid waste collection system, lack of proper solid waste treatment facility and recycling facilities, inadequate staff and funds for solid waste management authorities.

It is concluded from the study that

1. Major components of solid waste of Abbottabad are food, paper and plastics.

2. To treat food waste in Abbottabad, Composting is best with GHG emission reduction of 110% as compared to open dumping, landfill with LFG for energy recovery and open flaring, Anerobic Digestion and Incineration

3. For the treatment of paper and plastic waste of Abbottabad, recycling is best with emission reduction of 367% and 5317% respectively as compared to open dumping, Incineration landfill with LFG for energy recovery and open flaring.

4. Adopting the Composting for organic fraction of waste and Recycling for recyclable or inert fraction of solid waste would greatly reduce the GHG emissions and increase energy savings.

5. Rate of collection of solid waste is required to increased gradually by enhancing the capacity of solid waste management organization working in the districts. It can be done by provision of funds for purchase of equipment, awareness campaign and hiring of staff.

6. Rate of recycling and source reduction is required to be gradually increase to move towards the zero-waste strategy.

7. As far as the overall comprehensive solid waste management strategy for district Abbottabad is concerned, Scenario 9 is best with the GHG emission reduction of 154.7% and energy saving of 2727% as compared to the existing solid waste management strategy that is open dumping. In which an organic fraction of waste will be composted and other components will be recycled. paper plastic, metals, and glass through closed-loop recycling and concrete and electronics through open-loop recycling.

5.2. Recommendations for Policy Makers

In a nutshell, implementing a comprehensive solid waste management (SWM) strategy is essential for maintaining the beauty of Abbottabad, protecting the health of its residents and tourists, preserving the local ecosystem, and addressing Pakistan's climate change vulnerabilities. The following recommendations are offered to improve the current SWM practices in the district:

1. **Composting and Recycling Integration**: Composting should be incorporated to handle the organic fraction of waste, while recycling facilities need to be established for paper, plastic, metals, glass, concrete, and electronics. This will not only divert recyclable materials from landfills but also contribute significantly to GHG emission reduction and energy savings.

2. **Increase in Waste Collection Efficiency**: The current waste collection rate needs to be enhanced gradually by providing adequate funds to the solid waste management authorities. This funding should support the purchase of new equipment, capacity building, awareness campaigns, and the hiring of additional staff.

3. **Source Reduction and Waste Segregation**: Efforts should be made to promote waste minimization at the source and to encourage on-site waste segregation. Public education campaigns can help raise awareness about reducing waste generation and the importance of separating recyclables.

4. **Zero-Waste Strategy**: The district should aim to gradually increase recycling rates to align with a long-term zero-waste strategy. This would include expanding recycling

infrastructure and implementing source reduction initiatives, which will minimize waste generation at its origin.

5. **Infrastructure Development**: Investment in solid waste infrastructure, including composting and recycling facilities, waste transfer stations, and improved collection systems, is essential to meet growing waste management needs.

6. **Monitoring and Evaluation**: Implement a robust monitoring and evaluation system for SWM practices to track performance, ensure compliance with environmental standards, and identify areas for improvement.

7. **Public-Private Partnerships (PPP)**: Explore opportunities for public-private partnerships to leverage additional funding, expertise, and resources for efficient waste management. These partnerships can play a critical role in introducing advanced technologies and improving service delivery.

5.3. Recommendations for Future Studies

While this study has provided key insights into the current SWM practices in district Abbottabad, several areas warrant further exploration to enhance future research and policy development:

1. **Detailed Economic Feasibility Analysis**: Future studies should assess the detailed financial costs and benefits of implementing composting, recycling, and other waste treatment technologies. This would involve comparing capital investments, operational costs, and potential revenue streams from energy recovery or recyclable material sales.

2. **Waste Characterization Over Time**: A more comprehensive and longitudinal study on the composition of solid waste in the district is necessary to understand how waste streams evolve over time. This will help refine strategies to target different types of waste, especially in response to changing consumption patterns and population growth.

3. **Impact of Climate Change on Waste Generation**: Investigating the correlation between climate change and waste generation patterns could yield insights into how rising temperatures, precipitation changes, and extreme weather events influence the quantity and types of waste produced.

4. **Social Acceptance and Behavioral Studies**: Future research should delve into the behavioral aspects of waste management, including the public's willingness to adopt waste segregation practices, attitudes towards recycling, and the barriers to composting participation. Understanding these social dynamics will help in crafting more effective awareness campaigns and interventions.

5. **Life Cycle Analysis (LCA) Across Other Regions**: Replicating this LCA methodology across other districts or cities in Pakistan could provide a broader view of the SWM challenges in the country. Comparative analyses of urban and rural areas might reveal diverse solutions tailored to local contexts.

6. **Exploring New Waste Treatment Technologies**: Future research should explore the potential of advanced waste treatment technologies, such as gasification, pyrolysis, and plasma arc treatment, for handling specific waste streams in Pakistan. Evaluating the technical feasibility and environmental impacts of these technologies could open new avenues for sustainable waste management.

7. **Circular Economy Potential**: A deeper exploration of the circular economy's potential in Abbottabad's context is needed. Research could investigate how industrial symbiosis, product design for recyclability, and extended producer responsibility (EPR) could be implemented to close the material loop, reduce waste generation, and promote economic growth.

8. **Policy and Regulatory Framework**: Further studies could focus on the gaps and opportunities in Pakistan's waste management policies. An analysis of policy enforcement, incentives for recycling, penalties for illegal dumping, and the role of municipal and provincial authorities in waste management could guide future legislation.

9. **Exploring Waste-to-Energy Solutions**: Although composting and recycling offer significant environmental benefits, waste-to-energy (WtE) solutions could also be explored. Further studies could evaluate the potential of using WtE technologies in specific contexts where the organic fraction of waste might not be suitable for composting.

10. **Health Impacts of Current SWM Practices**: Future research should assess the

health implications of the existing open dumping practices, particularly in relation to leachate contamination of water bodies and the spread of diseases. Identifying and quantifying the health risks posed by poor waste management will provide critical data for advocating reform.

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