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ADDIS ABABA UNIVERSITY COLLEGE OF
BUSINESS AND ECONOMICS DEPARTMENT OF
ECONOMICS

Modelling Municipal Solid Waste GHG Emissions in Addis Ababa: A System Dynamics Approach

Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Master of Science in Economics (Applied Economic Modelling)

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Addis Ababa, Ethiopia

ADDIS ABABA UNIVERSITY
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DEPARTMENT OF ECONOMICS

APPROVAL SHEET

This is to certify that the thesis titled "Modeling Municipal Solid Waste GHG Emissions in Addis Ababa: A System Dynamics Approach" submitted by Robera Bayissa (GSR/9122/16) to the Department of Economics, College of Business and Economics, Addis Ababa University, in partial fulfillment of the requirements for the degree of Master of Science in Economics (Applied Economic Modeling) has been examined and approved.

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Declaration

I, Robera Bayissa Debela, hereby declare that this thesis proposal, entitled " Modelling Municipal Solid Waste GHG Emissions in Addis Ababa: A System Dynamics Approach" is my original work and has not been submitted for any degree or academic award at any university or institution. This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science in Economics (Applied Economic Modelling) at the Department of Economics, Addis Ababa University. I affirm that all sources of materials used for this work have been properly acknowledged.

Student: Robera Bayissa Debela

Signature:

Date: May 19, 2025

Abstract

This study employed a system dynamics model to evaluate greenhouse gas (GHG) emissions of municipal solid waste (MSW) management in Addis Ababa from 2022 to 2034 through the simulation of five treatment scenarios: Business as Usual (BAU), Organic Waste Diversion and Improved Sorting, Energy Recovery Maximization, Recycling-Driven Circular Economy, and a Combined Low Emission strategy. According to the BAU scenario led to faster saturation of the landfill and higher methane emissions, while Organic Diversion and Circular Economy scenarios achieved considerable emission reduction and jobs from recycling and composting. Energy Recovery Optimization scenario optimized incineration, reducing landfill usage but the CO_2 *hasn't declined as in the other policy scenarios despite the net cost increasing significantly. The Integrated Low Emission scenario with over 70% efficiency in separation, 25% recycling, 30% composting, and 40% use of waste-to-energy created the lowest overall GHG emissions, less than half of BAU by 2035, and produced the most sustainable outcome in all three aspects: environmental, economic, and social. These findings underlie the importance of integrated, low-emission waste strategies to facilitate a contribution from Addis Ababa to achieving Ethiopia's Climate Resilient Green Economy (CRGE) goals.*

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Contents

List of Abbreviation

AAEPGDC – Addis Ababa Environment Protection and Green Development Commission
AACMA – Addis Ababa City Management Agency
AACWMA – Addis Ababa City Waste Management Agency
AFOLU – Agriculture, Forestry and Other Land Use
AP – Allocation Proportion
BAU – Business As Usual
BOD – Biochemical Oxygen Demand
CH_4 – Methane
CLD – Causal Loop Diagram
CMOs – Cleansing Management Offices
CO_2 – Carbon Dioxide
CO_2e – Carbon Dioxide Equivalent
COP – Composting
CRGE – Climate Resilient Green Economy
CSA – Central Statistical Agency
EPR – Extended Producer Responsibility
EF – Emission Factor
EPA – Environmental Protection Authority
FDRE – Federal Democratic Republic of Ethiopia
GDP – Gross Domestic Product
GHG – Greenhouse Gas
GIS – Geographic Information System
GIZ – German Development Cooperation
GWP – Global Warming Potential
IN – Incineration
IPCC – Intergovernmental Panel on Climate Change
ISWM – Integrated Solid Waste Management

JICA – Japan International Cooperation Agency

kg – Kilogram

kWh – Kilowatt-hour

LD – Landfilling

LFG – Landfill Gas

MJ – Megajoule

Mt – Metric Ton

MSW – Municipal Solid Waste

MSWIN – Municipal Solid Waste Incineration

NGO – Non-Governmental Organization

NMVOCs – Non-Methane Volatile Organic Compounds

N_2O – Nitrous Oxide

SD – System Dynamics

SFD – Stock and Flow Diagram

SMEs – Small and Medium Enterprises

SWM – Solid Waste Management

UNEP – United Nations Environment Programme

UNFCCC – United Nations Framework Convention on Climate Change

UN-Habitat – United Nations Human Settlements Programme

WARM – Waste Reduction Model

WTE – Waste to Energy

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Chapter One

1. Introduction

1.1 Background of the Study

Municipal Solid Waste (MSW) refers to the everyday waste material thrown out by residential households, commercial establishments, institutions, and small industries in urban and suburban settings. MSW normally comprises food waste, paper, plastics, metals, glass, textiles, and garden trash. MSW control is a serious environmental and public health problem, especially in rapidly developing urban centers whose waste generation is on the increase. Effective MSW management constitutes a sequence of processes including collection, transportation, treatment, recycling, and final disposal, all of which require collaboration and green approaches. MSW understanding is essential to develop policies that mitigate environmental stress without compromising resources and public health (Kaza et al., 2018).

Urbanization, population increase, and industrialization are three primary drivers that contribute to the increasing production of MSW(Xiao et al., 2020a). In most developing and rapidly developing nations with urbanization, growing populations, and prosperity, municipalities are facing a major challenge in collecting, treating, recycling, and disposing of increasing volumes of solid waste and wastewater. One of the cornerstones of sustainable development is establishing affordable, effective, and genuinely sustainable waste management systems in developing nations. It should be reiterated that various cobenefits to public health, safety and the environment are realized from sound waste management practices that simultaneously minimize the greenhouse gas emissions and the environmental quality improvement, enhance the quality of life, ensure public health, avoid contaminating air, water and soil, save natural resources and offer renewable energy benefits(Bogner, J,et al., 2018). MSW treatment process consequently emits a large amount of greenhouse gases (GHG).

The waste sector is one of the largest human activity sectors accountable for the emission of greenhouse gases (GHG), particularly through the production of methane in landfills.The industry accounts for approximately 20.4% of overall methane emission, and therefore the third-largest source, lagging behind agriculture at 51.4% and fugitive emissions at 24.2%.While methane emissions due to the waste sector may seem comparatively small when weighted against overall GHG emissions, methane possesses a 20 to 30 times higher global warming potential than carbon dioxide. Consequently, these emissions are calculated to contribute to an increase in temperature by 1.5°C to 4.5°C over the next 40 years. In addition, in the 20th century, the Earth's surface temperature rose approximately 0.6°C(Sunarto et al., 2020). Waste generation in developing countries is growing at a rapid pace due to population and socio-economic development.

Infrastructure and systems for collection and safe disposal of waste, however, remain mainly non existent or severely lacking in most countries. Waste collection, treatment, and disposal activities are typically viewed from a cost centric perspective in developing countries, and along with poor or nonexistent environmental legislation, municipalities and local authorities have not given high priority to investing in these activities. Therefore, the generation of solid waste, open dumps, and environmentally degrading practices (such as open air garbage incineration or dumping off in water bodies) have become a problem of vast proportions in the majority of Asian and African urban centers. These trends are causing severe environmental degradation with the added ill effects on human health and well being(Siddiqi et al., 2020). The waste sector is responsible for around 8% of Africa's greenhouse gas emissions 2021, against 2% for the United States, 3% for China and 5% for France.

Nonetheless, in absolute terms, the African waste sector's emissions are over a third lower 36% than those of China. During the 2000-2021 interval, these emissions increased by 3% per year, i.e. twice the rate of growth of total .The biggest emitters in the waste sector within Africa are Nigeria 15%, followed by South Africa 8%, Algeria 7%, Egypt 7%, Morocco 7% and finally Ethiopia 6% and DR Congo 6%. For some ten African countries, waste sector emissions account for more than 10% of total emissions, e.g. Djibouti 21%, Morocco 19%, Comoros 16%, DR Congo 14%, Rwanda 14% and Gambia 13%. 21 %, Comoros 16 %, Congo 14 %, Rwanda 14 %, Gambia 13 % (Climate Chance Observatory, 2023). The growth of the urban population and the shift in consumption behavior in Ethiopia have led to a consistent rise in the production of municipal solid waste (MSW) all over the country.

Various studies attempted to make an estimate of the amount of MSW produced, and they reported different values ranging from 0.31 to 0.46 kg per capita per day. A recent government study that assessed 55 Ethiopian towns concluded that the per capita generation rate is approximately 0.31 kg/day with an average waste density of 241.8 kg/m³. Organic waste forms the majority, which accounts for 73%, and recyclable and reusable materials account for approximately 22%. Additionally, the study highlighted that national coverage of municipal solid waste collection and disposal is estimated to be 40% (Ministry of Planning and Development, Federal Democratic Republic of Ethiopia, 2020). Addis Ababa's waste management industry is one of the largest sources of greenhouse gases (GHG) at 13% (1,946,389 tCO2e) of total city emissions in 2016, with significant sources being solid waste disposal 43%, incineration and open burning 36%, and waste water treatment 21%.

The waste sector in Addis Ababa represents a significant source of greenhouse gas (GHG) emissions, contributing 13% (1,946,389 tCO2e) of the city's total emissions in 2016, with primary sources including solid waste disposal 43%, incineration and open burning 36%, and waste water treatment 21%. The city's reliance on unmanaged landfills, open burning practices, and limited composting infrastructure exacerbates methane and nitrous oxide emissions, particularly due to the high organic content (64%) of municipal waste. Notably, emissions from the waste sector increased by 13% compared to 2012, driven by reduced landfill usage and ineffective waste treatment methods, underscoring urgent challenges in waste management. This concerning trend highlights the critical need for robust modeling of waste related GHG emissions to identify mitigation strategies, optimize resource recovery, and align with Ethiopia's Climate Resilience Green Economy Strategy targets(AAEPGDC and C40 Cities, 2020).

In Addis Ababa City, the solid waste sector is a significant source of both formal and informal employment. Formally, 97 waste collection unions (SMEs) handle door-to-door waste collection, together employing 7,020 people (6,389 permanent members and 631 temporary contract workers), and these unions receive the majority (72.3%) of the city administration's annual waste related budget. In addition, Cleansing Management Offices (CMOs) at the 11 sub-cities and approximately 120 Woredas manage and supervise waste operations, each staffed by around 15 and 30 employees respectively. Composting and recycling SMEs such as 35 composting organizations handling organic market waste and firms recycling materials like paper, PET bottles, and metals contribute further employment, though specific workforce figures for these activities are not given. Informally, around 1,000 waste pickers work in hazardous and unregulated conditions at the Koshe landfill recovering recyclables, highlighting considerable issues of safety and job security for informal workers(AACMA & JICA, 2024).

This work aims to create a system dynamics model that measures and examines greenhouse gas emissions from Addis Ababa's municipal solid waste treatment processes. The project intends to find economically and environmentally sound methods that can help the city achieve its climate mitigation objectives by modeling various waste management scenarios, such as landfilling, composting, and incineration. The model helps policymakers make decisions by facilitating evidence based planning to lower emissions, increase the effectiveness of waste management, and support Ethiopia's Climate Resilient Green Economy (CRGE) Strategy.

1.2 Problem Statement

Handling of municipal solid waste poorly contributes to some of the largest and fastest-growing sources of human-caused greenhouse gas emissions, including methane (CH4), biogenic carbon dioxide (CO2), and non-methane volatile organic compounds (NMVOCs). Methane has a high global warming potential, being 28–36 times stronger than CO2 over a century, and atmospheric concentration is rising by 1–2% per annum. Landfills alone account for 3–9% of global anthropogenic methane emissions. There is typically a combination of 60% methane and 40% CO2 generated, with trace gases, from organic wastes in the landfills during anaerobic breakdown though the ratio varies depending on waste composition, their age, moisture levels, and the presence of hydrogen and oxygen available for their degradation(Ramachandra et al., 2018).

Disposal facilities are a significant GHG source of the waste industry, greatly driven by their higher organic content that breaks down anaerobically to generate LFG. LFG is primarily composed of methane (50–60%) and carbon dioxide (40–50%). As waste collection rates improve with time, GHG emissions will rise if waste is deposited in ill-managed landfills. A landfill has the ability to release GHG for decades (up to 30years) after it has been closed. In order to reduce such emissions, two key measures are suggested: divert organic waste away from landfill for future reuse and control LFG emissions (FDRE, 2020).

For several years now, waste production on the African continent has been rising steadily, driven in particular by demographic growth and galloping urbanisation. Combined with the expansion of the middle class, changing consumption habits are leading to an increase in waste production. In 2016, for example, sub-Saharan Africa produced 174 million tonnes (Mt) of household solid waste (hereafter MSW). Even though 70% to 80% of the waste is recyclable, only 4% is being recycled. According to African Clean Cities Platform estimates, by 2025 there will be waste production at 244 Mt. This poses a major challenge to the continent, despite there being waste management policies augmented with international regulation(Climate Chance Observatory, 2023).

Rapid population growth and increasing economic demands have placed significant strain on global resources, with 21st century urbanization transforming the world into a network of cities that, while improving quality of life, have also exacerbated environmental challenges particularly in solid waste generation due to rising consumption and disposable lifestyles. The United Nations estimates a 73% growth in world waste generation by 2050, at approximately 3.88 billion tons per annum, fueled by urbanization and population increases. Africa is hit by a serious waste management crisis even though it generates comparatively less waste compared to developed parts of the world, with Sub Saharan Africa's yearly waste levels more than doubling between 81 million tons in 2012 and 174 million tons in 2016 and set to reach 269 million tons by 2030. The continent, which has seen the fastest population growth in the world since the 1980s, only recovers 44% of its municipal solid waste, with more than 90% being disposed of in open and uncontrolled landfills where nearly half of the world's largest dumpsites are found, which presents catastrophic health and environmental hazards (Kassahun et al., 2025).

Despite rapid urbanization and economic growth, Addis Ababa faces mounting environmental challenges, particularly from the generation and management of municipal waste. In 2016 alone, waste emissions contributed 13% of the city’s total greenhouse gas (GHG) emissions, making the waste sector the second highest emitter after transport. The majority of these emissions source from solid waste disposal, open burning, incineration, and poor wastewater treatment. According to the statistics, solid waste and incineration make up over 79% of total sector emissions(AAEPGDC and C40 Cities, 2020).

However, the data quality on waste composition and treatment practices remains low, and systematic modelling for how various waste management strategy impacts GHG emissions is still lacking. This study aims to fill these gaps through modeling the GHG emission pattern of existing and alternative waste treatment practices in Addis Ababa with a view to inform targeted mitigation measures and support the city's overall climate action agenda in accordance with the Climate Resilience Green Economy Strategy (CRGE). The research will provide a quantitative foundation to assess the potential impact of improved waste management interventions on the reduction of GHG emissions and guide evidence based policy decisions for a sustainable urban future. In addition to that, The Reppi WTE plant in Addis Ababa, Ethiopia, faces significant operational challenges that hinder its capacity to achieve planned energy production targets. Designed to incinerate 1,400 tons of solid waste daily and generate 50 MWh of energy per day (18,250 MWh annually), the plant currently processes only 600 tons/day, producing 15.7

MWh/day (5.73 million kWh annually) a 69% shortfall in waste intake and a 69% deficit in energy output.

Both these interconnected systemic failures cause this underperformance such as, Inadequate segregation of waste, whereby all the waste gathered is dumped unsorted, resulting in poor quality feedstock and lower incineration efficiency (attaining only 26.17 kWh/ton compared to the planned 35.7 kWh/ton) and Inefficient management practices such as poor workforce planning, lack of proper technical skill, and inability to expand operations to achieve the 1,400 tons/day goal. Such problems are further aggravated by deeper institutional issues like low public knowledge and insufficient investment in professionalism of the waste sector. Lack of waste segregation and systemic inefficiency not only erodes energy recovery but also sustains dependence on unsustainable landfilling, aggravating the environmental and urban health hazards(AACMA & JICA, 2024).

1.3. Research Objective

1.3.1 General Objective

To develop a system dynamics model that quantifies and evaluates the greenhouse gas (GHG) emissions from municipal solid waste (MSW) management in Addis Ababa, and to simulate the environmental and socioeconomic impacts of alternative treatment scenarios for informing sustainable waste management policies.

1.3.2 Specific Objectives

- ✓ Using city-level waste data and established emission factors, calculate the current GHG emissions from Addis Ababa's MSW sector.
- ✓ To create a dynamic simulation model that reflects the interplay between population growth, treatment procedures, waste generation, and policy interventions.
- ✓ To model various waste treatment processes, such as landfilling, composting, recycling, and incineration, and examine the expected effects on greenhouse gas emissions, system expenses, and job creation.
- ✓ To identify optimal policy interventions that balance environmental sustainability (GHG mitigation) with economic and social outcomes, aligned with Ethiopia’s Climate Resilient Green Economy (CRGE) strategy.

1.4. Significance of the study

This study is of significant contribution in meeting the rising environmental concerns of greenhouse gas (GHG) emissions from municipal solid waste (MSW) of Addis Ababa. Due to rapid urbanization and population growth, the volume of generated solid waste has been increased tremendously, which caused environmental as well as public health issues. Through development of a system dynamics model to estimate and compare GHG emissions for main MSW treatment options composting, incineration, and landfilling this research provides timely insight into the environmental implications of current and emerging waste management practices.

The results of the study are expected to benefit policymakers, waste managers, and environmental planners in developing evidence-based and sustainable treatment plans for managing waste. Measuring of the emissions through different treatment routes, the model helps identify cleaner alternatives with lower GHG emissions and aid Ethiopia's climate change obligations for mitigation under the Paris Agreement and national environmental policy goals. Secondly, this study contributes to the growing body of literature on waste sector emissions in the urban developing world, with a replicable methodology that other cities with similar waste management problems can adopt.

1.5 Organization of the study

The study is structured into five chapters to discuss systematically the greenhouse gas (GHG) emissions modeling of municipal solid waste (MSW) management in Addis Ababa. Chapter One presents the study by providing the background, problem statement, research aims, and the justification of why the study matters. Chapter Two will be presenting the overview of literature related to the topic, including theoretical foundations and empirical studies on solid waste management and GHG emissions. Chapter Three presents the methodology, including modeling process, data sources, and the computer models utilized in estimating GHG emissions from different waste treatment processes. Chapter Four discusses the system dynamics simulation outcomes, compares the emission profiles of various treatment processes, and provides a comprehensive discussion of the results. And finally Chapter Five summarizes the research by presenting main findings, offering policy recommendations, and suggesting areas of further study toward the facilitation of improved sustainable waste management and climate change mitigation in urban Ethiopia.

1.6 Research Question

What is the impact of different MSW treatment strategies composting, incineration, and landfilling on GHG emissions in Addis Ababa, and which strategy or combination offers the most environmentally sustainable outcome by 2035?

1.7 Scope of the Study

Using 2021 as the base year and projecting through 2034, this study aims to model greenhouse gas (GHG) emissions from Addis Ababa's municipal solid waste (MSW) management. It compares the greenhouse gas emissions of the three main waste treatment methods landfilling, incineration, and composting. Variables like population growth, emission factors, treatment capacities, and waste generation rates are all included in the model. In order to assist in the decision making process for a low emission waste management strategy in the city, the objective is to evaluate the environmental effects of both the current and alternative waste management scenarios.

Chapter Two

2. Literature Review

2.1Theoretical review

2.1.1 Waste Hierarchy Theory

The hierarchy of waste is arguably the simplest SWM principle, with a hierarchy system to manage waste that centers around prevention as the most desirable and disposal as the least There are six levels in the hierarchy: prevention, minimization, reuse, recycling, energy recovery, and final disposal. This concept encourages practices that prevent waste generation at the source, e.g., by designing products for minimal packaging or using reusable products. Recycling and energy recovery such as in the form of WTE incineration is regarded as intermediate actions, while landfilling is seen as a measure of last resort. This hypothesis is the foundation of most national and urban waste management policies and encourages sustainable consumption and production patterns(Yakubu & Zhou, 2019).

2.1.3 Integrated Solid Waste Management (ISWM)

ISWM is a comprehensive system which considers the entire waste cycle and the integration of multiple waste treatment and disposal options .(Tchobanoglous & Kreith, 20)It is concerned with the interaction between technical components (e.g., collection, treatment, and disposal) with the institutional, social, and economic components. Government authorities to the informal waste sector stakeholder participation is a significant consideration, especially in developing countries. ISWM also takes into consideration the local context so that solutions are specific to social, cultural, and economic conditions in particular. The method encourages sustainability through balancing environmental protection, economic viability, and social acceptance.

2.1.3 Circular Economy Theory

Circular economy model shifts from the traditional linear economic model of "take, make, dispose" to one where resources are kept in use for as long as possible, extracting maximum value from them before recovery and regeneration at the end of each service life (Ellen MacArthur Foundation, 2013). From the SWM's point of view, the theory lays emphasis on product design that supports reuse, repair, remanufacture, and recycling. Waste is transformed into resource in the closed loops, for example, through recycling of plastics to fresh products or via composting of organic waste. The circular economy is also expressed in policy like Extended

Producer Responsibility (EPR), whereby producers are held accountable for the entire life cycle of their products(Kirchherr et al., 2023).

2.1.4 Systems Theory in Waste Management

Systems theory sees solid waste management as a complex system with several actors, processes, and feedbacks (Jha et al., 2024). It accounts for factors such as generation of waste and policy regulation, treatment processes such as segregation, collection, and treatment, and outcomes such as recovered material and residual waste. A System thinking is also important in the determination of inefficiencies or bottlenecks along the waste management chain. By analyzing the interdependency of elements ranging from citizen habits to institutional performance this theory allows for the optimization of complete systems rather than individual components.

2.1.5 Behavioral Theories (e.g., Theory of Planned Behavior)

Behavioral theories, particularly the Theory of Planned Behavior (Ajzen, 1991), are key to understanding how individuals and groups behavior affects waste management practices. Under this theory, behavior is influenced by attitudes (individual views about recycling), subjective norms (what one thinks other people expect), and perceived behavioral control (ease or difficulty of recycling). These findings are utilized to structure awareness campaigns, education interventions, and policy levers to affect sustainable behavior, such as household waste segregation or composting. Behavior theories are most useful when participatory community engagement is critical for successful implementation of SWM programs.

2.1.6 Zero Waste Theory

Zero Waste theory advocates the prevention of waste by product and system redesign that prevents trash from being produced(Connett, 2013).It focuses on source reduction, sustainable product design, and the development of large-scale recycling and composting facilities. Policy instruments in this strategy tend to discourage landfills and incinerations by promoting alternatives such as producer take back schemes and community based sorting initiatives. Zero Waste plans have been adopted by San Francisco and other municipalities, with the aim of sending nearly all waste to landfills by having aggressive recycling and composting targets.

2.1.7 Environmental Justice Theory

Environmental Justice Theory prioritizes equitable distribution of environmental costs and benefits, particularly among marginalized and vulnerable groups (Stewart, 1991).In waste management, it talks about how landfills, incinerators, and other waste facilities are disproportionately located in poor or minority communities. Environmental Justice Theory focuses on inclusive decision-making processes and policy reforms to ensure that everyone has an equal level of protection from environmental hazards. It is important in providing fair access to waste services and the protection of human rights in SWM system design.

2.2. Empirical Literature Review

2.2.1 Municipal Solid Waste

Municipal Solid Waste (MSW) is defined as a heterogeneous mixture of discarded materials generated by households, commercial establishments, and institutional entities, encompassing organic matter, plastics, paper, metals, glass, and inert materials (Amasuomo & Baird, 2016). The European Union's legislative framework classifies MSW broadly to include not only household waste but also commercial waste that shares similar characteristics, reflecting regional lifestyles and consumption patterns. MSW management is a critical environmental challenge, particularly in urbanized areas, due to its high organic content and inefficient disposal practices such as open dumping and uncontrolled incineration, which contribute to methane emissions and public health risks. The complexity of MSW composition varying significantly across cities and countries demands context specific management strategies, including recycling, composting, and energy recovery, to mitigate environmental degradation and align with sustainability goals. The subjective nature of waste classification, where materials deemed useless by one entity may serve as resources for others, further underscores the need for standardized definitions and regulations to guide effective waste governance and infrastructure development(Amasuomo&Baird,2016)

There are significant variations in the MSW composition between municipalities and between countries. This variance is mostly influenced by lifestyle, economic conditions, waste management laws, and industrial structure. The amount and makeup of municipal solid waste are important factors in determining how these wastes should be handled and managed. The majority of the municipal solid trash produced in developing nations comes from homes (55–80%), with markets and commercial sectors coming in second (10–30%). The other is produced by streets, businesses, institutions, and numerous other sources(Abdel-Shafy & Mansour, 2018).

2.2.2 Green House Gas

Greenhouse gas emissions refer to the release of heat trapping gases into the atmosphere, which contribute to the greenhouse effect and global climate change. The primary greenhouse gases include carbon dioxide, methane, nitrous oxide, and fluorinated gases. These gases vary in their global warming potential and atmospheric lifespan, but all contribute to rising global temperatures. Human activities such as fossil fuel combustion, industrial processes, deforestation, agriculture, and waste management are major sources of greenhouse gas emissions. The increase in these gases, especially since the industrial revolution, has intensified the natural greenhouse effect, resulting in more extreme weather, sea level rise, and ecological disruption(IPCC, 2023).

In the context of solid waste management, methane is particularly significant due to its high warming potential and prevalence in landfill emissions. When organic waste decomposes without oxygen, such as in landfills or untreated waste dumps, it releases methane into the atmosphere. Inadequate waste management infrastructure in many cities, especially in developing countries, worsens these emissions. Addressing greenhouse gas emissions from waste requires integrated strategies such as improved waste collection, recycling, composting, and energy recovery methods like incineration with emissions control. Reducing greenhouse gases from the waste sector not only helps mitigate climate change but also improves urban health and sustainability (UNEP 2022).

2.2.3 Municipal Solid Waste and its Environmental Impact

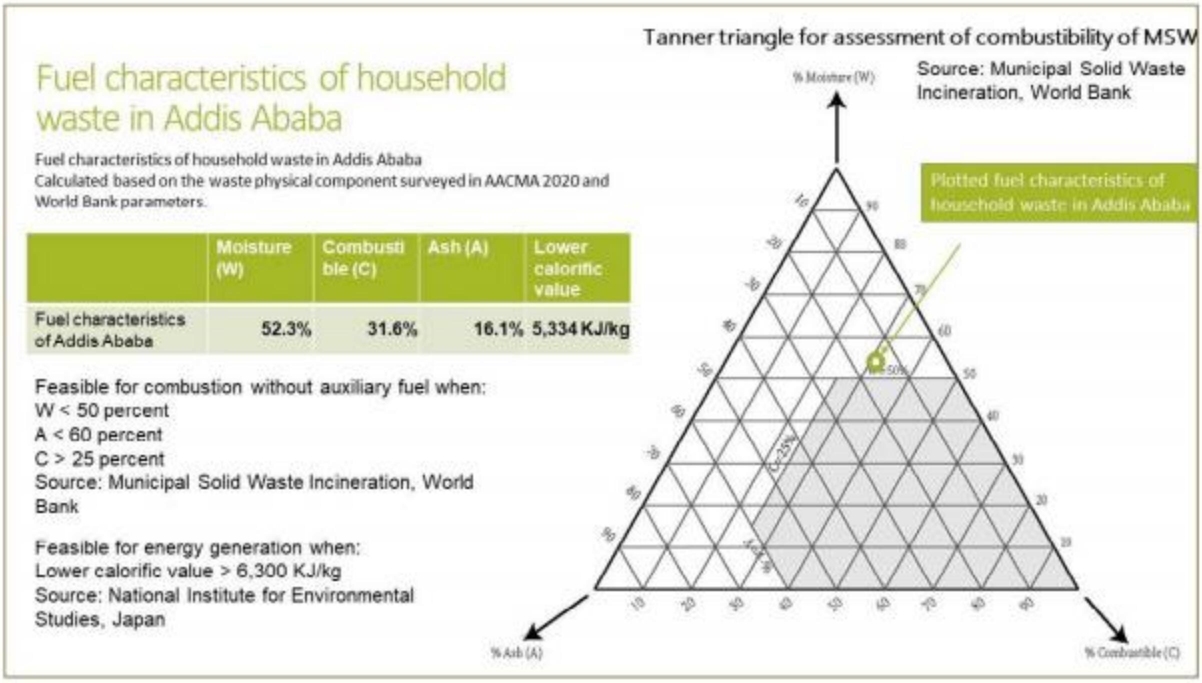
The World Bank's 2012 report, What a Waste: A Global Review of Solid Waste Management, provides a comprehensive analysis of the relationship between municipal solid waste (MSW) management and greenhouse gas (GHG) emissions. The report highlights that landfills are significant sources of methane emissions, a potent GHG with a global warming potential 21 times greater than carbon dioxide. Specifically, methane from landfills accounts for approximately 12% of total global methane emissions. The level of methane emissions varies by country, influenced by factors such as waste composition, climatic conditions, and waste disposal practices. For instance, in South Africa, methane emissions from post-consumer municipal waste disposal are estimated at 16 million tCO2e, constituting 4.3% of the country's total GHG emissions. The report underscores the importance of implementing effective waste management strategies, such as landfill gas capture and utilization, to mitigate these emissions. This insight is particularly relevant for rapidly urbanizing cities like Addis Ababa, where the expansion of MSW generation necessitates the adoption of sustainable waste management practices to reduce GHG emissions and combat climate change.

The contribution of landfills to global greenhouse gas (GHG) emissions, particularly methane, which possesses a global warming potential 28–36 times greater than carbon dioxide over a century. The study underscores that methane emissions from landfills are a critical concern due to their substantial impact on climate change. Furthermore, the authors emphasize the importance of implementing effective waste management strategies, such as landfill gas capture and utilization, to mitigate these emissions. This insight is particularly relevant for rapidly urbanizing cities like Addis Ababa, where the expansion of municipal solid waste generation necessitates the adoption of sustainable waste management practices to reduce GHG emissions and combat climate change (Zhang et al., 2019).

2.2.4 Waste to energy

Waste to energy is internationally recognized as a powerful tool to prevent the formation of greenhouse gas emissions and to mitigate climate change. The international panel on climate change (IPCC) has recognized waste to energy as the key greenhouse gas emission mitigation technology. Over the years, there have been a number of quantitative assessments made to compare the environmental benefits associated with the processing of MSW in WTE facilities rather than disposing of MSW in landfill. A state of the art WTE facility is roughly estimated by most models to save CO2 in the range of 100 to 350 kg CO2 equivalent per ton of waste processed. Recently, markets have developed around the world to compensate WTE operators for the reduction in the CO2 emissions. Currently, this CO2 credit is higher in developing countries due to poor landfill practices. Further, the more efficient the WTE facility, the more CO2 credit it will generate(Fraol Alemu, 2019).

In comparison with developed countries that have sophisticated approaches to the classification of waste, Addis Ababa City's MSW classification system is not yet started and poorly developed. Its MSW has a lower heat value because of its relatively higher organic composition and moisture content, so it achieves lower energy efficiencies when incinerated. The average heat value of MSW in developed countries waste incineration plants is 8.4–17 MJ/kg. But studies showed that in developing countries where classification and separation of waste is less practiced the average heat value of MSW is by far less than developed countries. Because the waste contains many organic substances and nutrients, it is difficult to recycle the heat generated in the incineration process; the generated heat may be lost as smoke, which itself requires purification(Massreshaw Assnakew, 2018).



Fuel characteristics of household waste in Addis Ababa

Fuel characteristics of household waste in Addis Ababa
Calculated based on the waste physical component surveyed in AACMA 2020 and World Bank parameters.

	Moisture (W)	Combustible (C)	Ash (A)	Lower calorific value
Fuel characteristics of Addis Ababa	52.3%	31.6%	16.1%	5,334 KJ/kg

Feasible for combustion without auxiliary fuel when:
W < 50 percent
A < 60 percent
C > 25 percent
Source: Municipal Solid Waste Incineration, World Bank

Feasible for energy generation when:
Lower calorific value > 6,300 KJ/kg
Source: National Institute for Environmental Studies, Japan

Tanner triangle for assessment of combustibility of MSW

Source: Municipal Solid Waste Incineration, World Bank

Fig 2.1 Fuel Characteristics of Household waste in Addis Ababa(AACMA & JICA, 2024)

2.2.5 Municipal waste Landfills

Municipal waste, which includes both residential and commercial refuse, is a substantial source of CO2 emissions and waste streams. Landfills, the principal disposal sites for urban waste, contribute to greenhouse gas emissions via the anaerobic decomposition of organic matter, which produces methane a greenhouse gas substantially more potent than CO2 (Kiehbadroudinezhad et al., 2024). While municipal waste incineration lowers volume, it emits CO2 and other pollutants, contributing to air pollution and climate change (Choi & Rhee, 2024).

Landfilling is a prominent and cost-effective form of disposal of waste in several African countries (Idowu et al., 2019). In landfills, microorganisms degrade waste in the absence of oxygen, resulting in leachate and landfill gas (LFG) (Choi & Rhee, 2024).The rate of decomposition is determined by temperature, moisture, waste content, and waste age LFG is composed of up of 50–60% methane (CH4), 40–50% carbon dioxide (CO2), 2–5% nitrogen, less than 1% ammonia, and trace amounts of oxygen, non-methane organic compounds sulfides, hydrogen, and carbon monoxide. In 2016, the global municipal solid waste (MSW) was approximately 2.01 billion tons, with forecasts of 3.4 billion tons by 2050. Economic expansion, population growth, and urbanization are all predicted to contribute to increased waste generation. Unfortunately, at least 33% of this trash is disposed of openly and not in an environmentally acceptable manner (Mbazima et al., 2022).

2.2.6 System Dynamics Modeling of Solid Waste Management and Environmental Impact

In recent years, system dynamics (SD) has been increasingly utilized to model the environmental implications of municipal solid waste (MSW) treatment methods, particularly regarding greenhouse gas (GHG) emissions, land degradation, and air and water pollution. Given the complex and interdependent nature of waste management systems, SD enables researchers to simulate long-term environmental outcomes under various policy and infrastructure scenarios. This makes it a valuable tool in assessing how treatment strategies such as landfilling, incineration, composting, and recycling affect emissions and sustainability goals.

(Rafew & Rafizul, 2021) developed an SD model for Khulna City, Bangladesh, incorporating waste generation, collection, treatment, and landfill capacity alongside environmental indicators. Their analysis showed that if investments in treatment infrastructure did not increase, environmental degradation would intensify due to higher volumes of untreated waste and overflowing landfills. Their model emphasized that composting and diversion strategies significantly reduce pollution and methane emissions.

In a study by (Dianati et al., 2021)an SD model was applied in Kisumu, Kenya, to assess GHG emissions from residential solid waste. Two scenarios were examined: the introduction of a waste-to-biogas initiative and the enforcement of a ban on open waste burning. The model projected a reduction of 1.1 million tons of CO2 equivalent emissions by 2035, primarily through the use of biogas to displace polluting fuels. This study demonstrated the critical role of organic waste diversion in climate change mitigation.

(Retuerto et al., 2021) used SD to evaluate the environmental effects of improper waste treatment in Lima, Peru, where open dumping and insufficient recycling were prevalent. Their simulations showed that improving waste sorting and composting could reduce solid waste accumulation by over significant tons by 2030, with corresponding reductions in methane emissions and leachate pollution. The findings underscored the ecological value of waste minimization at the source.

Similarly, (Wang & You, 2021) modelled the connection between waste separation and environmental performance in Tianjin, China. Their study demonstrated that increasing the separation of food and recyclable waste substantially reduced landfill loads and associated emissions. The GHG mitigation benefits were tied directly to the amount of waste diverted from landfills to more sustainable treatment methods.

(Xiao et al., 2020b)constructed a comprehensive SD model that incorporated the environmental impact of MSW treatment policies in China. Their findings indicated that economic development directly increases per capita waste generation, but that the adoption of biochemical treatment technologies, such as anaerobic digestion and advanced composting, was vital to curbing methane and CO2 emissions from waste. The model stressed that landfills remained the largest source of GHG emissions unless controlled by capture technologies or offset through diversion.

In the Malaysian context, (Zulkipli et al., 2016) used SD modelling to show how increasing recycling rates reduced waste volumes and improved environmental outcomes. Their stock flow analysis revealed that investment in recycling infrastructure was strongly correlated with a decline in pollution and energy consumption associated with waste incineration and landfilling.

Among recent studies in Ethiopia, the work by (Yalelet Tadesse, 2024)stands out as a detailed application of system dynamics to model the environmental impacts of municipal solid waste in

Despite these contributions, there remains a notable gap in SD models that focus explicitly on GHG emissions from solid waste treatment in Sub Saharan African cities, particularly in Ethiopia. Most existing studies have not modelled emissions from Addis Ababa's waste sector under diverse treatment scenarios such as land filling with gas capture, incineration with energy recovery, or decentralized composting systems.

This research addresses that gap by applying a system dynamics framework to quantify and compare the environmental impacts of current and alternative waste treatment strategies in Addis Ababa, particularly their GHG emissions profiles. The model aims to support climate-aligned decision-making by showing how improved waste treatment can significantly contribute to Ethiopia's Climate Resilient Green Economy (CRGE) goals while reducing pollution and protecting urban ecosystems.

2.3 Literature Gap

From the literature that has been read, while system dynamics has been applied in modeling municipal solid waste management and its impacts on the environment in most urban cities, including a study conducted in Bahir Dar, Ethiopia, there is a specific and broad gap concerning Addis Ababa. Previous research did not explicitly model greenhouse gas emissions from Addis Ababa's waste sector using a system dynamics approach with different treatment scenarios such as landfilling, energy recovery from incineration, or decentralized composting plants. This absence of a system dynamics model encompassing in some detail the different GHG emission profiles of the alternative waste management strategies in Addis Ababa is a primary gap in the literature, constraining the development of aimed, evidence-based policies for climate change mitigation in the waste management sector of the city.

2.4 Conceptual frame work

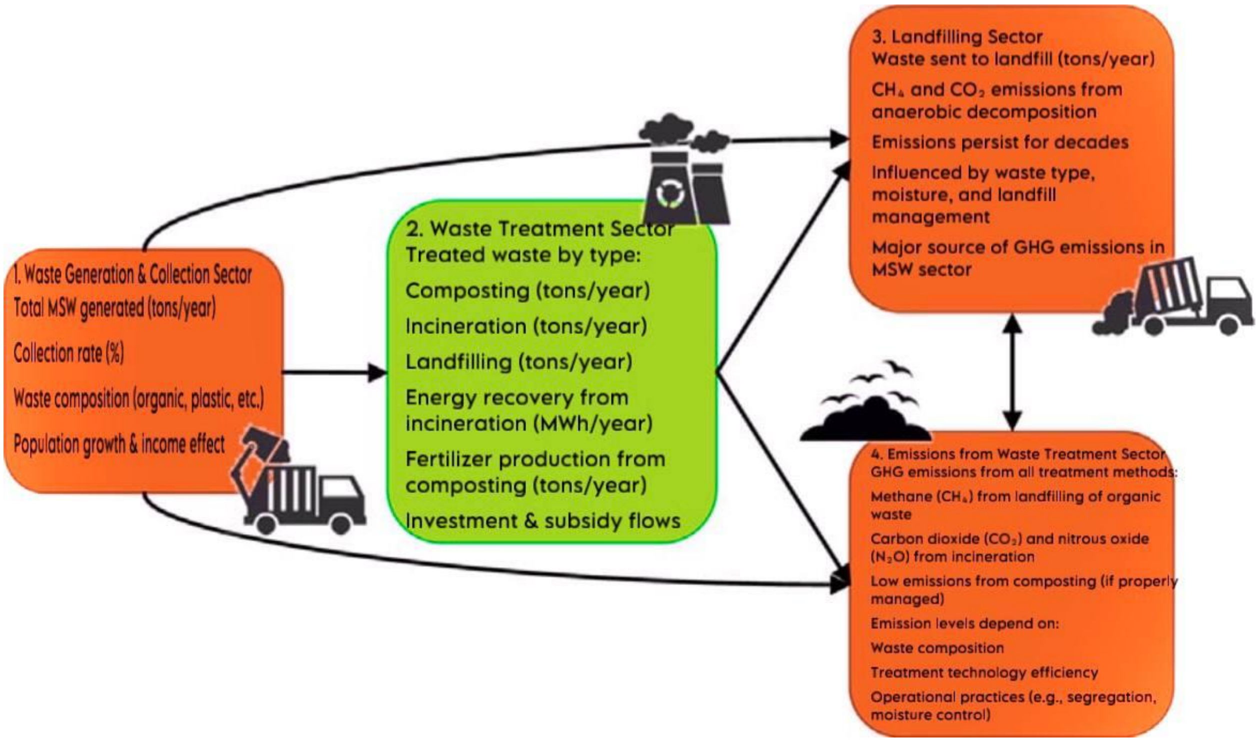


Fig 2.2 Conceptual frame work of the MSW generation, collection, treatment and its emission

This conceptual framework outlines the MSW management life cycle across four interconnected sectors. It begins with the Waste Generation & Collection Sector that quantifies total waste produced, collection rate, and composition based on population and economic expansion. The Waste Treatment Sector then defines treatment methods composting, incineration, and landfilling along with outputs like energy recovery and fertilizer, supported by investments and subsidies. The Waste Treatment Sector evaluates GHG impacts, landfill CH4, incineration CO2 and N2O, and negligible composting emissions, whose intensities depend on waste composition, technology efficiency, and practice. Finally, the Landfilling Sector emphasizes the importance as a major GHG source, driven by anaerobic microbial breakdown of organic waste, with emissions lasting for decades and controlled by waste type, moisture, and management. Together, the structure provides a holistic view of MSW flow, treatment efficiency, environmental impact, and socio economic drivers and enables analysis of emissions reductions and improved sustainability measures.

Chapter Three

3. Research Method

3.1 Approach and Data source

3.1.1 Approach

The study utilizes a system dynamics modeling approach to evaluate the economic and environmental impacts of Addis Ababa municipal MSW management in terms of GHG emission. The system dynamics approach is utilized for its ability to model complex and interacting systems with feedback loops and time delays. Because systems of solid waste are complex in nature and comprise waste generation, treatment options, routes of emission, as well as policy actions, the aforementioned approach provides an appropriate environment to model long-term behavior and policy reactions.

Model construction begins with problem formulation and conceptual model design. The basic model structure introduces the essential components of the MSW system, including population growth, waste generation, waste composition, treatment alternatives (landfilling, composting, and incineration), and corresponding emissions. Feedback loops are also brought in to account for dynamic feedbacks, such as the effect of increasing waste generation on landfill capacity, treatment demand, and environmental burden.

The model is built and simulated with Vensim PLE software that allows causal relationships and feedback effects to be viewed and analyzed over time. Scenario-based simulations are executed to compare the outcomes of different waste management practices. For example, scenarios can assess the impact of expanding composting capacity, expanding waste to energy incineration, or upgrading collection and segregation rates on overall GHG emissions and system costs.

The iterative modeling practice involves validation and simulation phases to check for conformity to observed data and trends. The final product is both a research tool as well as a decision-support system for policymakers and planners. It provides insight into the contribution of current practices toward long-term sustainability and deals with leverage points for reducing emissions, optimizing utilization of resources, and improving environmental performance of Addis Ababa's waste management

3.1.2 Data source

Research data comprises predominantly of secondary data gathered from institutional reports, literature, and field observation. These data are generated from the following major sources:

- ✓ Municipal Solid Waste Data: Waste generation rate, waste composition, collection efficiency, and treatment technology data are used from official city-level reports of the Addis Ababa City Administration, Sanitation and Beautification Agency, and joint appraisal by AACMA and JICA.
- ✓ Environmental Data: Global warming potentials, emission factors, and green house gas estimation methodologies are based on the IPCC Guidelines, UNEP assessments, and published greenhouse gas inventories for Addis Ababa.
- ✓ Technical and Operational Information: Treatment capacity facility figures, energy from incineration, composting efficiency, and waste composition are drawn from facility-specific reports on the Reppie WTE facility, composting facilities, and the Koshe dumpsite, supplemented by technical reports published.
- ✓ Socioeconomic and Economic Statistics: National reports, planning documents, and publications by international development agencies are used to provide estimates for population growth, GDP, waste industry employment, and investment levels.
- ✓ Literature and Case Studies such as Peer-reviewed scientific papers and case studies of modeling solid waste management, GHG emissions, urban African and global system dynamics applications provide conceptual guidance and references for model calibration were used.

3.1.3. Analytical Tools

Vensim software is used by the study to simulate and develop the model. Statistical tools are employed to validate the model using historical data, thereby making it predictive accurate for forecast purposes

3.2 Study Area Description

Addis Ababa is the capital and largest city of Ethiopia and is the country's political, economic, cultural, and administrative center. The city is located in the geographical center of Ethiopia at an elevation of between 2,200 and 3,000 meters above sea level and has an area of approximately 527 square kilometers. Addis Ababa is a chartered city and is at the same time a city and a regional state with direct reporting to the federal government.

The population of Addis Ababa has been growing exponentially over the past two decades. The city had a population of approximately 2.7 million in 2007, according to the national census. Recent estimates place the figure at approximately 5.2 million in 2022, and over 6 million by 2030(CSA, 2019). This growth is largely driven by large rates of rural-urban migration, economic opportunities, and natural increase. Thus, the city is experiencing huge stress on infrastructure and public facilities, as for example, housing, transport, sanitation, and most especially solid waste management.

Addis Ababa is decentralized administratively into 11 sub cities (kifle ketema), which are further divided into 117 woredas (districts). The sub cities include Addis Ketema, Akaky Kaliti, Arada, Bole, Gullele, Kirkos, Kolfe Keranio, Lideta, Nifas Silk Lafto, Yeka, and Lemi Kura. They are distinct from one another in terms of population density, infrastructure development level, and access to waste management services. The Addis Ababa City Administration governs the city, and the Sanitation and Beautification Agency primarily coordinates solid waste management services.

Addis Ababa generates a tremendous volume of municipal solid waste due to its large population and rapid urbanization. The city is estimated to produce over 3,000 tons of waste daily with the majority of it being organic waste. Repi landfill (commonly known as Koshe) on the south western outskirts of the city is the primary wastage disposal site. By the projects such as the Reppie waste to energy plant and city-wide composting schemes have been introduced, the city remains reliant on landfilling. So that increasing generation of waste with no sufficient treatment and recycling capacity poses a serious environmental problem, such as the release of greenhouse gases like methane. This study seeks to analyze these dynamics so that it can understand the overall environmental impact of Addis Ababa's present and future waste disposal.

3.3 Dynamic Hypothesis

The generation of municipal solid waste (MSW) in Addis Ababa increases day by day. This is largely attributed to the growth in population, rapid urbanization, and improving living standards. As production increases with the waste, added pressure is imposed on the city's waste management infrastructure. The size of the pressure is defined by the quantity of waste

The majority of waste in Addis Ababa is taken to landfills while a small amount is treated through composting or incineration. Since the majority of the waste ends up at landfills or open dumping sites, methane (CH4) emission due to anaerobic decay primarily makes up the biggest portion of GHG emissions from the waste sector. The composition of the waste, particularly the content of organics, is a critical factor behind the emissions.

The limited treatment capacity, poor segregation at the source, and poor recycling rates are also responsible for the accumulation of untreated organic waste in landfills. Besides contributing to rising methane emissions, environmental and health risks also rise. Conversely, expanding the capacity of composting and incineration plants can reduce landfill bound waste and hence the subsequent emissions. However, treatment operations all possess an emission profile of GHGs, with incineration producing CO2 and nitrous oxide (N2O) but normally lower per unit than methane from landfill.

3.4 Casual Loop Diagram

Causal loop diagram is a fundamental tool in system dynamics that visually represents the feedback relationships within a system. It illustrates how different variables interact over time through positive and negative feedback loops, highlighting the dynamic and interconnected nature of complex systems. In a causal loop diagram, arrows indicate the direction of influence between variables, with positive arrows signifying reinforcing relationships (where an increase in one variable A leads to an increase in another) and negative arrows indicating balancing relationships (where an increase in one variable results in a decrease in another). This diagrammatic approach helps stakeholders understand system behavior, identify leverage points for interventions, and anticipate unintended consequences, making it a valuable asset in fields such as organizational management, environmental science, and public policy. By visualizing intricate interdependencies, causal loop diagrams facilitate a deeper understanding of the systemic nature of issues, promoting more informed decision making.

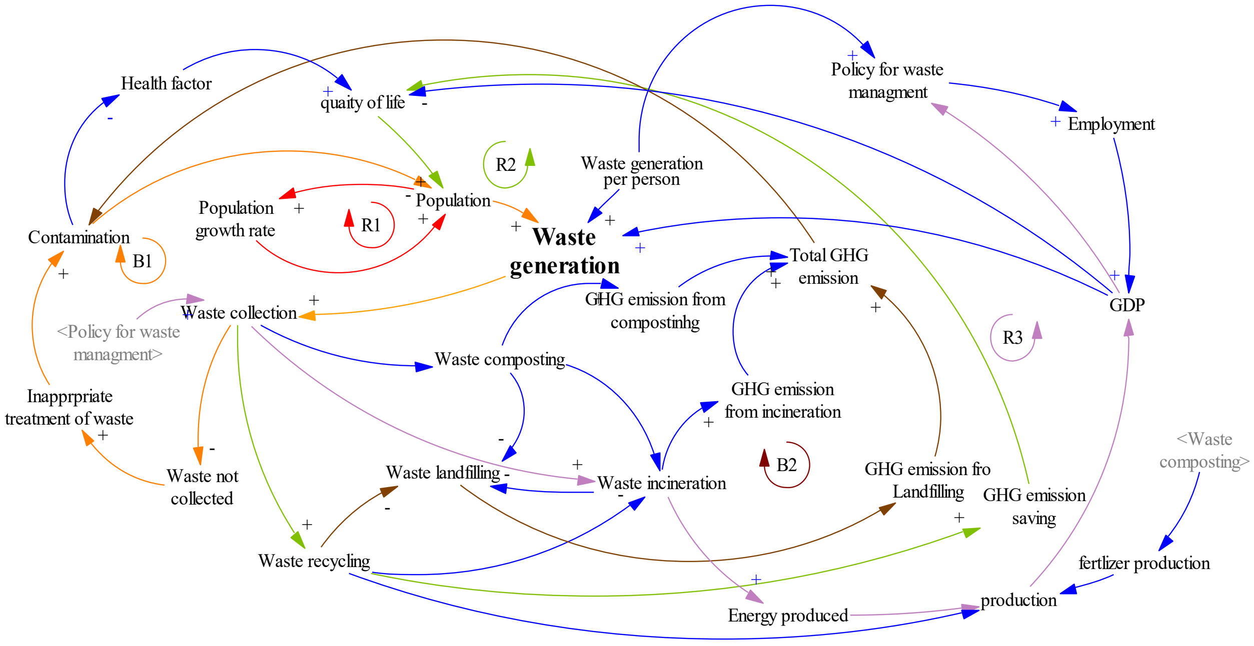


Fig 3.1: A causal loop diagram (CLD) representing the model

In this casual loop diagram, Waste generation is the initial event that generates most of the subsequent processes and dynamics. It is the introduction of waste into the system, triggered by the combined effect of the Population size and the Waste generation per person. An increase in this event puts pressure on the waste management infrastructure and has various environmental and socio-economic effects depicted in the diagram. The quantity of waste produced directly dictates the amount to be collected and processed through composting, landfilling, incineration, or recycling. Waste generation, therefore, plays a vital role in setting the downstream consequences and activities in motion in the system.

Reinforcing Loop R1 (Population and Population Growth Rate): The loop portrays the reinforcing connection between population and population growth rate. With increasing population, it strives towards an increased population growth rate via natural increase and possibly migration from rural regions as a result of urban pull. This, in turn, leads to further population growth, developing a reinforcing loop. This loop demonstrates the exponential growth nature of the population growth in the lack of any check and how population pressure can exacerbate waste disposal and city planning problems.

Reinforcing Reinforcing Loop R2 (Waste Recycling and Quality of Life):the loop shows how more recycling of waste leads to GHG emissions savings, which leads to improved environmental quality and, subsequently, quality of life. Improved quality of life leads to more people moving into the city, thereby increasing the population and, subsequently, waste generation. But when recycling facilities are improved in parallel with the concomitant production of trash, larger quantities of trash are redirected from reaching toxic dump, affirming a cycle of positive environmental effect and city appeal. This cycle recognizes the potential of sustainable processes to create synergistic beneficial effects on the environment and human health.

Reinforcing Loop R3 (GDP, Policy, and Energy Production): is a positive loop where economic wealth can provide the means for enhancement of waste disposal, and this, in turn, fund further economic growth.It begins with GDP growing, providing financial room for better Policy towards waste disposal. Improved policy leads to better Waste collection, more being able to go to Waste incineration. This cycle generates Energy generated, which drives overall economic Production. Higher levels of production then feedback into higher levels of GDP, completing the positive feedback loop. This feedback loop suggests that investments in waste-to-energy technology and good waste management infrastructure can create a virtuous cycle in which economic growth and environmentally sustainable management of resources support one another to some degree, perhaps resulting in continued growth and better system performance.

Balancing Loop B1 (Waste Collection and Contamination): It starts with population and waste generation.As waste generation is increased, more waste needs to be collected. As waste collection is low, more waste is not collected and leads to higher pollution of the environment. Pollution of the environment negatively affects health and urban quality of life, which can decrease the population growth rate or trigger corrective policies. The loop thus operates to balance the system by balancing contamination through control via improved waste collection and management infrastructure.

Balancing Loop B2 (Landfilling, Emissions, and Population Pressure): Loop B2 is aimed at the environmental effect of landfilling.Since more wastes are being generated and are landfilling, emissions and pollution rise. Such environmental degradation has potential adverse effects on health and living standards, which can decelerate population growth or even result in shrinking populations. The loop acts as a brake on uncontrolled wastes and landfilling, demonstrating the environmental impact of unsound waste management systems and resulting in shifts towards more environmentally friendly waste treatment technologies.

3.5 Stock flow Diagram

Stock Stock and flow diagram is a core component of system dynamics modeling that depicts the accumulation and flow of resources between a system over time. It distinguishes stocks and flows that are rates at which these amounts change (e.g., rate of daily recycling or waste collection). Diagramatic approach enables dynamic behavior modeling, particularly how systems evolve as a function of the inflows and outflows with each stock.

Stock and flow diagrams are most useful for measuring system behavior, scenario simulation, and studying policy impacts over time. In waste management, to name one example, this approach can be employed to simulate how municipal solid waste piles up, sorted, recycled, composted, or dumped in landfills based on system capacity and behavioral factors like sorting effectiveness or coverage of collection.

Structuring of systems in rate based movement and accumulation, stock and flow diagrams provide a more precise and actionable image than causal loop diagrams alone. They are particularly valuable when coupled with simulation tools such as Vensim, enabling decision makers to run experiments on the long term effects of policy measures and to observe where bottlenecks, oversaturation, or inefficiencies will arise.

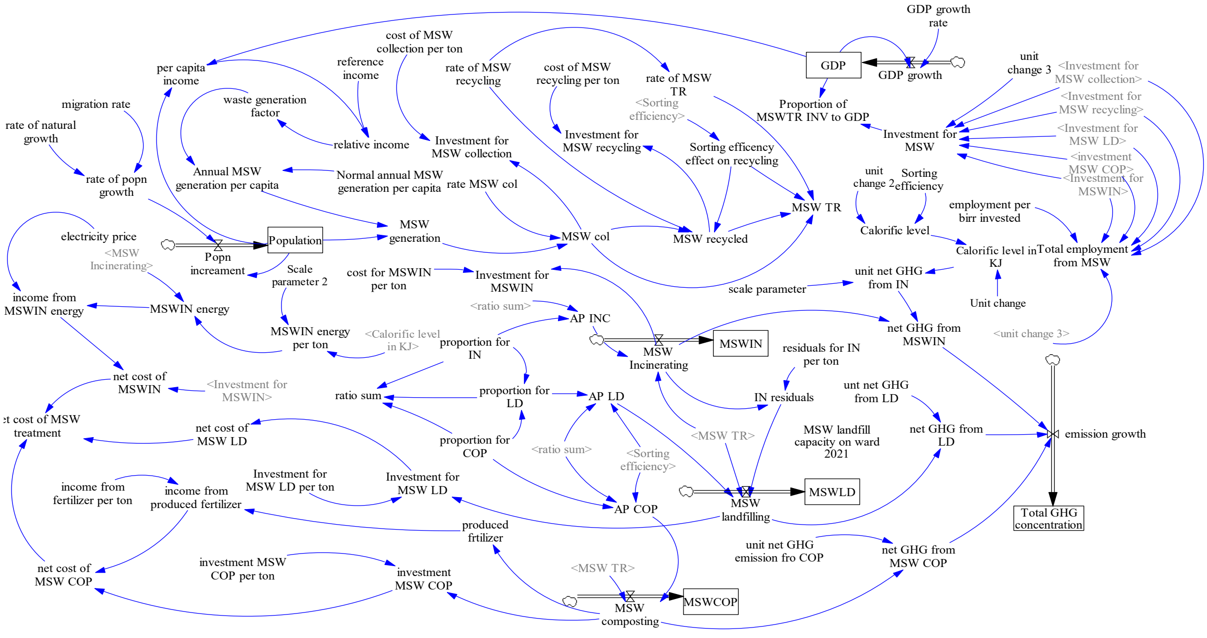


Fig 3.2: A Stock flow diagram (SFD) representing the model

3.5.1. Definition of Variables

Municipal Municipal Solid Waste (MSW): MSW refers to the household waste materials discarded by the general public on a daily basis, for example, food waste, packaging materials, paper, plastics, textiles, and yard waste. In the case of Addis Ababa, MSW is characterized by organic waste and inadequate formal waste segregation at the source.

Landfilling: MSW disposal where the waste is capped in specially constructed landfill sites. Landfilling in Addis Ababa is a common mode of disposal, often without the incorporation of methane capture systems. It is characterized by high methane emissions due to anaerobic decomposition of organic wastes.

Waste to Energy (WTE) Incineration: It involves the combustion of MSW to generate electricity. Reppie WTE plant in Addis Ababa is a significant plant in this respect. Though it reduces the volume of waste, it emits greenhouse gases, mainly CO2, depending on waste composition and combustion efficiency.

Composting: A biologically mediated process in which biodegradable waste is converted into nutrient-rich compost. Composting, if properly practiced, produces low green gas emissions and keeps organic waste out of landfills, thus reducing methane generation.

GHG Emissions (tCO_2e): Greenhouse gas emissions in metric tons of CO2 equivalent. The variable adds up the global warming impact of methane, carbon dioxide, and nitrous oxide emitted by the different waste treatment operations. It is one of the key indicators to evaluate the environmental efficiency of MSW management.

Share of Waste Treatment: The portion of MSW that has been treated in different ways (landfilling, incineration, composting). This determines the emissions profile of the urban waste management sector and depends on infrastructure, policy, and awareness.

Waste Recycling Share: Waste recycling refers to the gathering, sorting, and treatment of MSW materials that can be re-used or re-manufactured as new products. Recycling in this model focuses on recovery of materials such as plastics, metals, paper, and glass by formal and informal systems. Recycling waste bypasses the conventional treatment processes (landfilling, composting, or incineration), reducing the impact on the environment and using fewer resources.

Recycling is defined in terms of direct output from collected wastes, i.e., the quantity collected is equivalent to the total of waste treated (through landfilling, composting, or incineration) and recycled waste.

3.6. Solid Waste Generation and Emission Profile in Addis Ababa

3.6.1 Waste Generation and Collection in Addis Ababa

Waste Generation and Collection in Addis Ababa The population of the city of Addis Ababa, which stands at over 5.2 million as of 2022, generates approximately 3,300 tonnes of municipal solid waste (MSW) daily, or roughly 1.97 kg of waste per capita per day (JICA, 2024). This per capita generation rate is among the highest in the area. With the urban sprawl and population increasing further, so does the volume of generated waste. Even though the waste collection in the city reaches most of the central areas through municipal and private operators, the collection is not comprehensive, especially in periphery and informal settlement zones. An important percentage of waste goes uncollected or gets eliminated by open burning and informal dumping.

3.6.2 Waste Treatment and Management Practices

In terms of waste management practices, Addis Ababa still relies largely on landfilling. The Koshe landfill is the major destination for the city's solid waste and is an uncontrolled, open dump facility with no installation of methane capture systems or management of leachate. Other treatments are minor in size and scope. The Reppie Waste to Energy (WtE) plant was built to reduce landfill dependency through burning of MSW to generate electricity. However, its operation is strongly limited by the high water content and low calorific value of the feed waste, both of which are being aggravated by the lack of pre sorting. Composting is done by a limited number of small-scale industrial units capable of treating only a minute proportion of organics approximately 24 tonnes per day whereas informal recycling is concentrated on high-value materials like PET, scrap metal, and cardboard Improving inefficiencies in sorting would enhance treatment efficiency, reduce emissions, and achieve value in recyclable and compostable waste streams.

3.6.3 Emissions from Waste Treatment Methods

Waste sector contributed around 13% of total emissions, as per the city's 2016 GHG inventory, which was just behind transportation in magnitude. The majority of the emissions resulted from landfilling and open burning, as a result of uncontrolled decomposition of organic waste and lack of methane capture facilities.

While the transport sector leads the city's emission profile, the contribution of the waste sector is not negligible, given the emission-saving potential of low-cost measures like composting, enhanced sorting, and recycling. Unlike industries like stationary energy (8%) and AFOLU (1%), waste remains an important and controllable source of GHG emissions.

3.6.4 Cost of Waste Treatment

Addis Ababa waste management is very expensive in terms of collection, transportation, disposal, and treatment. Landfilling, although by definition low cost, involves long term health and environmental consequences involving unforeseen expenditure. The Reppie WtE power plant, despite being set up to reduce landfill dependency, experiences inefficient performance due to the poor quality of waste feedstock (high water content, low calorific value), which also makes treatment more expensive.

Most significantly, enhanced efficiency in sorting would reduce treatment cost by Reducing waste requiring incineration or landfilling, Enhancing quality of composting feedstock and Creating value from recovered materials.

3.6.5 Employment in the Waste Sector

The waste disposal industry in Addis Ababa supports both informal and formal employment. Informal operators in thousands are engaged in collection, street sweeping, and waste picking, notably at Koshe. Small scale recycling and composting enterprises also provide employment, notably to low income groups.

Waste policies that encourage recycling, composting, and sorting have potential high employment multipliers. They are light on technology and infrastructure but have enormous potential for job creation particularly in comparison with mechanized or centralized treatment options like incineration.

Chapter 4

4. Model validation and Behavior analysis

4.1 Model Structure Test

Without examining the connections between structure and behavior, model structure tests enable us to evaluate the parameters and structure of the model. A model's structure can be evaluated using a variety of tests; in this study, the structure and parameter verification tests, dimensional (unit consistency test), and extreme condition tests are conducted to increase confidence in the model's structure(Forrester, 1992).

4.1.1. Structure and Parameter Verification Test

The parameter test and structure test is the most critical stage in validation of a system dynamics model. As argued by (Forrester, 1992) the test involves two aspects: verification of whether the structure of the model accurately reflects the real world system it is intended to replicate, and verification of whether the constant parameters used in the model agree with empirical data, expert judgment, or available literature.

In Chapter Three, under the model description and hypothesis, the structure of the model as a stock and flow model was mentioned. The structure identifies the dynamic relationships among key variables, which together produce the observed behavior of Addis Ababa municipal solid waste management system. The model includes processes such as generation of waste, distribution of treatment (landfilling, incineration, composting), emissions, cost, and employment implication.

All the constant parameters utilized in the model were also defined and justified based on available sources. Validity of the model then lies upon two conditions: the ability of the structure of the model to represent the real world system as it is, and the correctness of the parameter values defining the behavior of the model.

To meet these needs, both model structure and parameter values were developed and validated by an interactive process of expert consultation and literature review. Specifically, relevant research papers, organizational reports from institutions such as JICA and Addis Ababa City Administration, publicly available GHG inventories, and official web pages were consulted to conceptualize the model. Additional qualitative checking of assumptions and numerical estimates and contextual appropriateness were obtained through expert consultation and expert practitioner consultation.

This process of validation ensures that the model design is grounded on theoretical understanding as well as experiential knowledge, thus making it more trustworthy for scenario analysis and policy simulation in the case of Addis Ababa municipal solid waste treatment.

4.1.2. Dimensional Test

Consistency of units in the process of building a model can be used as a means of model validation test. The units must be consistent throughout the model and must exactly represent the intended variables. The consistency of all the units is checked in the model and some of the variables along with their units are presented below.

	Variable Name	**Unit**
1	Annual MSW generation per capita	tons/(year*person)
2	Calorific level	KJ/KG
3	cost of MSW collection per ton	birr/tons
4	emission growth	tCO2e/year
5	GDP	Birr
6	MSW generation	tons/year
7	MSWIN energy per ton	MWh/tons

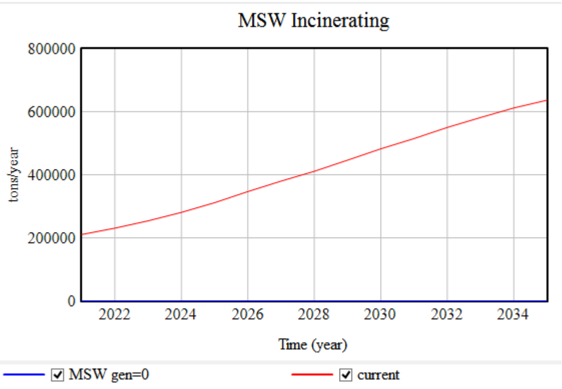
Table 4.1 some important ariables with their unit

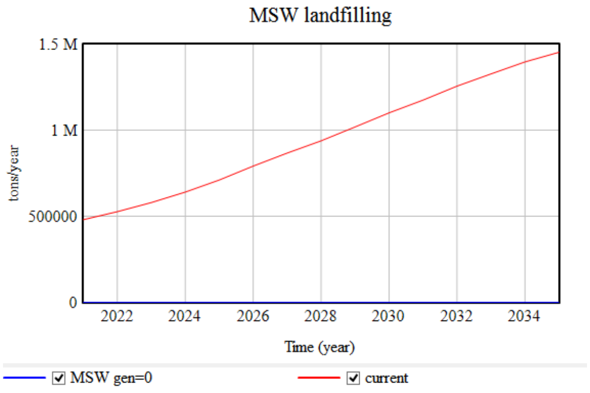
4.1.3 Extreme Condition Test

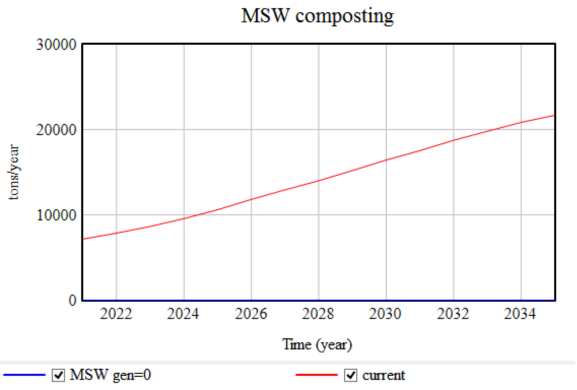
Extreme condition testing is a critical component of system dynamics model validation. It is used to examine the behavior of the model when given highly exaggerated or unrealistic input values, to verify if the model behaves sensibly and predictably. Although the test cases employed may never occur in real conditions, this test is meant to verify if the model structure holds up in edge conditions and behaves as expected from expert knowledge of the system.

Extreme condition test is employed for this study to simulate the variable for the rate of municipal solid waste (MSW) generation. Waste generation is one of the key drivers of the model, influencing waste treatment distribution, greenhouse gas (GHG) emissions, system total cost, and employment in the waste value chain. In an attempt to check the robustness of the model, extreme instances of waste generation are simulated: a zero waste scenario.

For this case, the generation rate of waste is decreased to zero, that is, there ought not to be any generation of waste. Here, the model is expected to behave as it should: waste that is dumped in landfill, composting, and incineration should all drop to zero. These translate into the complete elimination of emissions from all treatment processes since there is no waste that can decompose, burn, or process. Moreover, the cost of waste management must be going down to zero since there are no collection, transportation, and treatment costs. The employment for the waste industry also disappears in such a scenario, particularly for labor based activities such as sorting, composting, and waste handling. The model's performance under this limiting condition is consistent with the reasoning of an actual operating waste system and justifies the internal consistency of the structural assumptions.







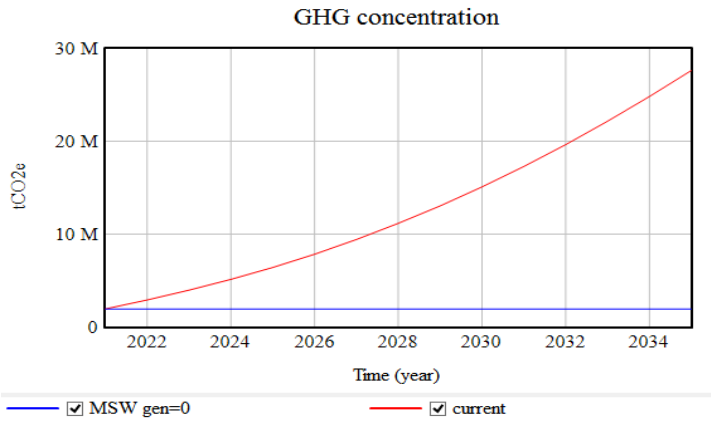


Fig 4.1 Extreme condition test for different waste treatments and Total GHG emission from MSW.

4.1.4 Boundary Adequacy Test

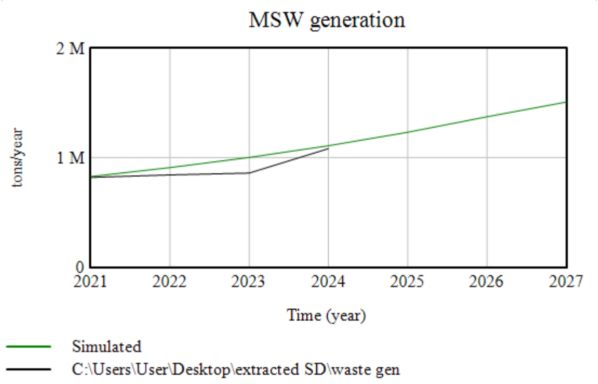
This test is about whether or not the policy-relevant results would have been significantly different if the model's boundary had been extended or contracted (Forrester, 1992). In defining its scope, the model has purposely included the major flows and stocks of municipal solid waste, generation, collection, composting, incineration (WtE), and landfilling, and their direct greenhouse gas emissions, while at the same time excluding processes such as informal waste picking dynamics, water-borne leachate emissions, and detailed transport logistics that are peripheral. The boundary adequacy test checks if these exclusions might influence the results of the scenarios or the proposed interventions.

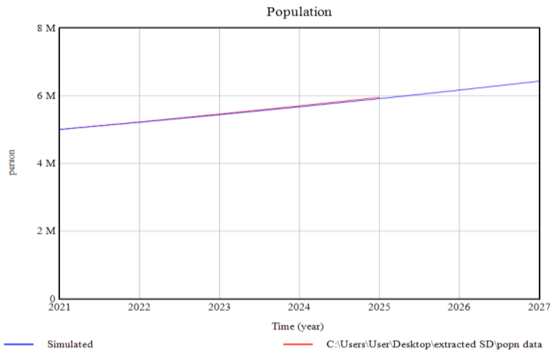
Firstly, we investigate the non-inclusion of the informal recycling sector. Even though informal collectors recycle high-value material (e.g., PET, metals), their work is not directly represented in the model. An extension of the boundary to cover the informal recycling feedbacks—where the recovered material both reduces the volume of the waste going to the landfill and decreases the demand for formal treatment—might lead to the change of the best policy mix toward higher investment in community sorting incentives (AACMA & JICA, 2024) . Nevertheless, these sensitivity tests show that filing out the informal recycling sector with an additional 5–10% of waste diversion would not change the relative ranking of composting versus incineration scenarios, implying that the main policy implications are still very good to this boundary extension. Secondly, the model does not take into account methane capture technologies at already existing landfills. Putting into the model a landfill-gas capture loop would create a balancing feedback effect—reducing CH_4 emissions but at the same time there would be more capital cost. Initial investigations show that a CH_4 capture rate of up to 50% can cut the GHG in the BAU scenario by 15–20%, however, it does not change the fact that the integrated diversion strategies are still better than landfill alone (IPCC, 2023) .

Thirdly, the boundary is limited to the direct emissions from transport and the construction of facilities. Adding the embodied emissions will raise the carbon footprint of all treatment options more or less equally and hence the relative benefits of waste diversion and recycling will still be maintained. Hence, although expanding the model limit may improve the accuracy of emission estimates, it still does not change the main finding: the measures that focus on sorting sources, composting, and recycling are the most effective in reducing GHG emissions during the period from 2022 to 2034.

4.2. Model Behavior Test

Testing behaviors generated by the structure of a model help us evaluate the adequacy of the structure. In this section, among the various tests of model behavior, we consider mainly two of them: behavior reproduction (comparison between simulated and Reference behavior) and sensitivity analysis.


MSW generation


Population

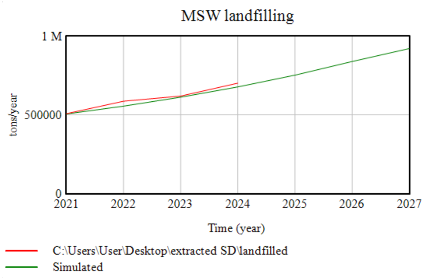

MSW landfilling

Fig 4.2 Behavior test for selected variables

4.2.2 Behavior sensitivity test

The Behavior sensitivity test is one of the main aspect of system dynamics model verification. The test checks the sensitivity of the model's outputs to changes in the values of key parameters and establishes the model's stability and robustness. According (Forrester, 1992), while the absence of high sensitivity may enhance confidence in the model structure, sensitivity in certain variables doesn't disprove the model. Instead, it highlights the policy applicability of those variables in real-world decision making. Three sensitivity analyses of behavior are experimented on in this study in order to determine the response of the model to variations in municipal solid waste (MSW) generation rate, sorting efficiency, and recycling rate. Each experiment is performed by varying the selected variable within a 50% confidence interval, and the results will be presented in the format of simulation results.

The first sensitivity test is on MSW generation rate, which is the incidence or main driver of the entire waste system.By changing the waste generation rate per annum, we analyze its impact on Total GHG emissions, net MSW treatment cost and wastes landfilling. When the waste generation rate is increased, the model must show a corresponding rise in emissions and treatment costs due to the increased quantity of waste entering the system. Landfilled waste will also be greater under lower sorting and recycling levels, causing methane emissions to rise significantly. A lower waste generation rate, on the other hand, should cause reductions in all of these output variables, which demonstrates the sensitivity of environmental and economic results to the degree of waste generation.

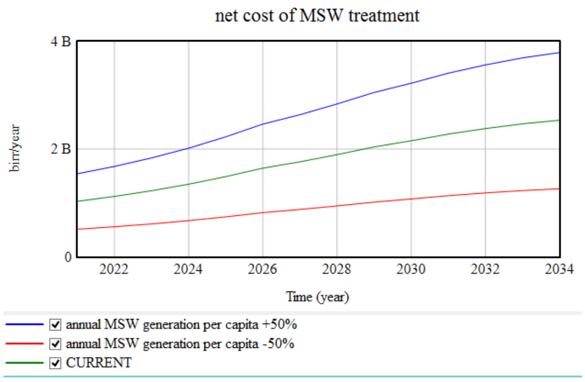
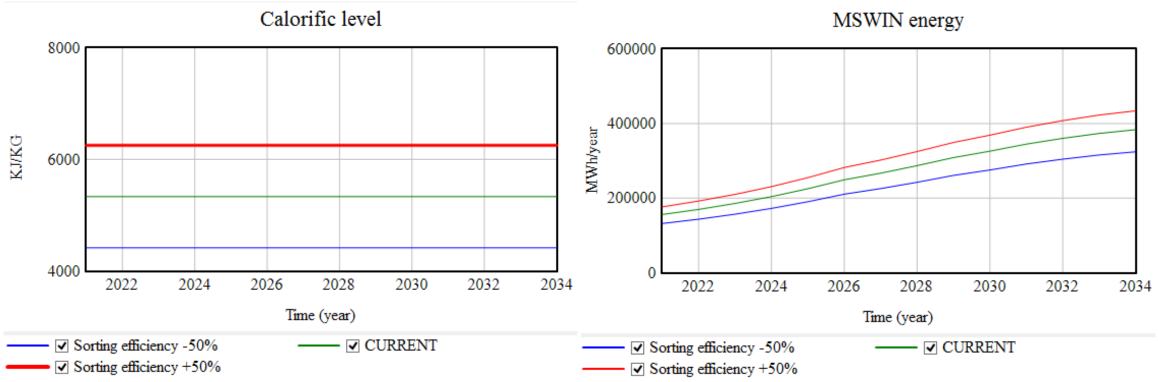


Fig 4.2 Sensitivity of MSW generation rate for on Total GHG emissions, net MSW treatment cost and MSW landfilled

The second test examines the sensitivity of the model to changes in sorting efficiency, The analysis evaluates the effect of changes in sorting efficiency on calorific value of waste, energy produced per ton of waste, energy produced from Incineration, and overall GHG concentration within the system. Sorting efficiency increase is expected to increase the calorific value of the waste stream that is sent for incineration and hence improve the combustion efficiency and reduce the net emissions. Meanwhile, better sorting allows more organic waste to go to composting, once more reducing landfill emissions and overall GHG load. less sorting efficiency, on the other hand, leads to a mixed waste stream with high moisture content that reduces energy yield and increases emissions from incineration and landfilling.



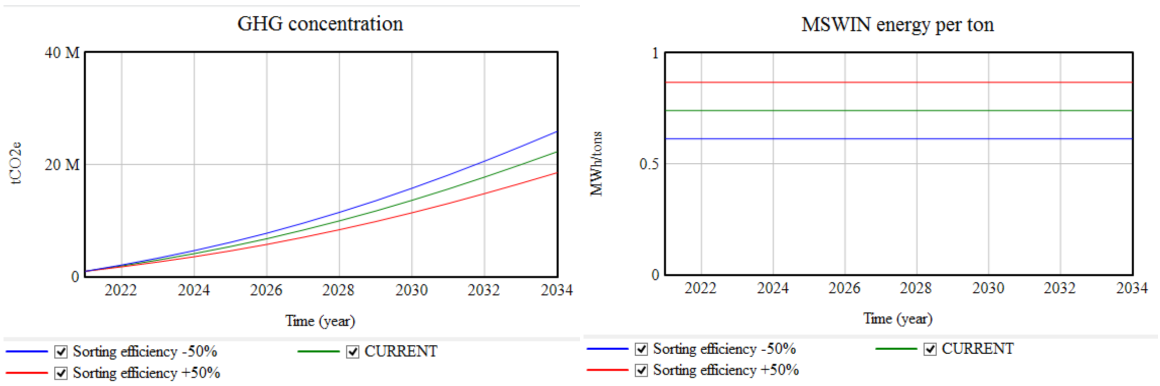
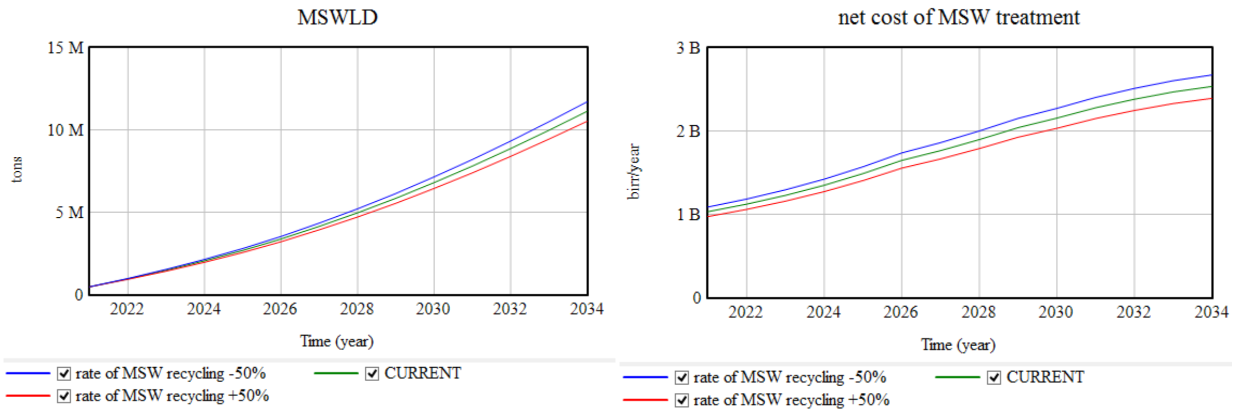


Fig 4.3 sensitivity of sorting efficiency on waste calorific level, produced MSW incineration energy and Total GHG concentration.

The third sensitivity test is aimed at the recycling rate, which is a crucial parameter for material recovery and emissions reduction.This test analyzes the effect of changes in recycling rate on the amount of waste landfilled (MSWLD), net cost of MSW treatment, and total GHG concentration. The recycling rate increases waste avoidance that is landfilled and incinerated and, as a result, reduces both methane and CO_2 emissions. It also lowers the net cost of treatment by diverting waste from more expensive disposal activities to more sustainable material recovery processes. Reduced recycling equals greater pressure on landfilling and incineration systems and therefore greater emissions and operational cost. These sensitivity analyses were conducted to show the response of the model to parameter value changes. The results will provide a sense of which variables have greatest influence in determining emissions, cost, and system performance, and will guide the identification of key points of leverage for waste management policy in Addis Ababa.



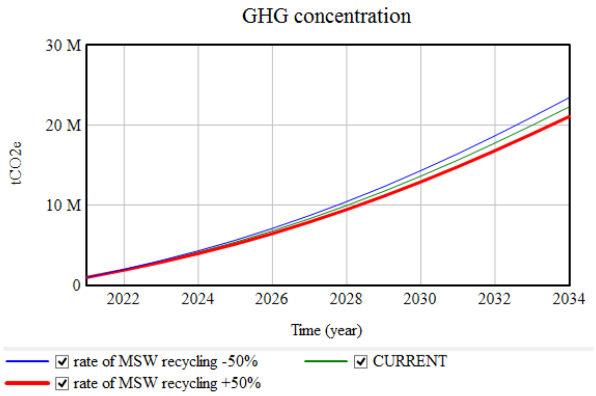


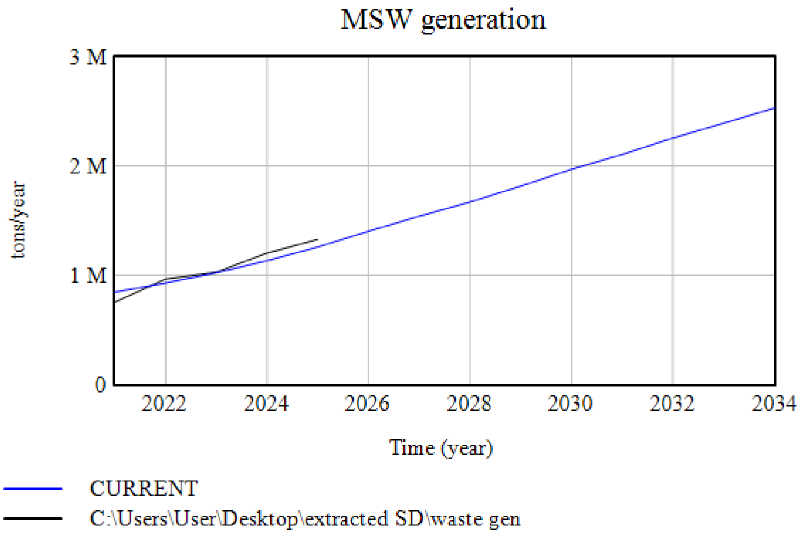
Fig 4.4 sensitivity test of recycling rate on waste landfilled (MSWLD), net cost of MSW treatment, and Total GHG concentration.

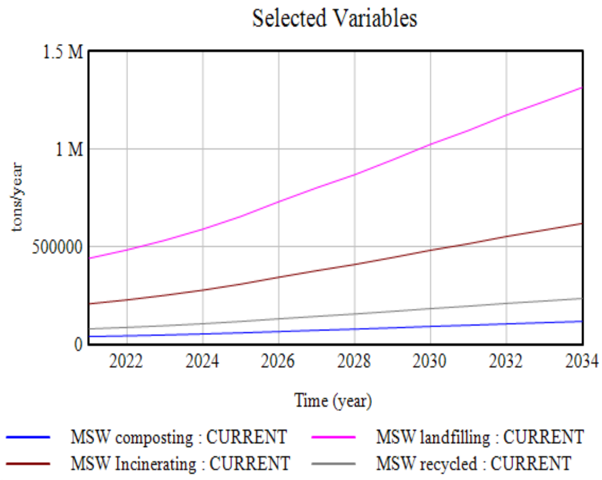
These sensitivity analyses were simulated to illustrate the model's response to parameter variation. The results will provide insight into which variables are most influential in shaping emissions, cost, and system performance, and will support the identification of key leverage points for effective waste management policy in Addis Ababa.

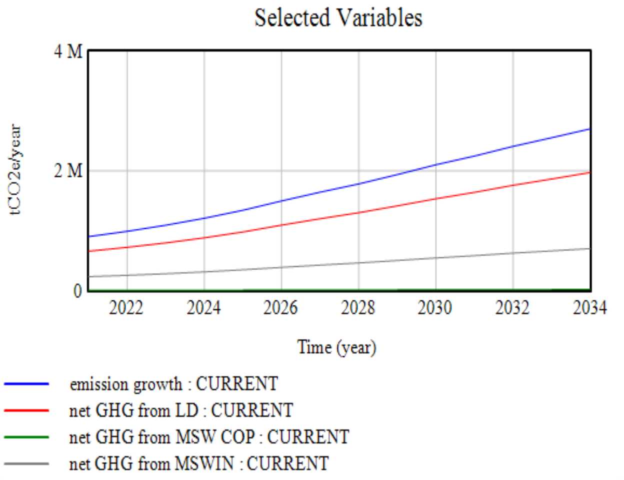
4.3 Possible Scenarios

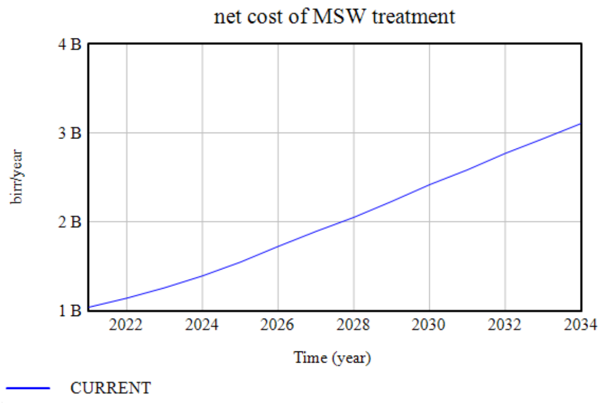
Scenario based modelling is employed to assess environmental and economic effects of various alternative municipal solid waste (MSW) management strategies in Addis Ababa using the system dynamics model developed. The scenarios forecast future system dynamics under different assumptions for waste treatment ratios, sorting efficiency, recycling percentages, and institutional investments. The scenarios allow evidence based planning towards a low emission, resource efficient urban waste system.

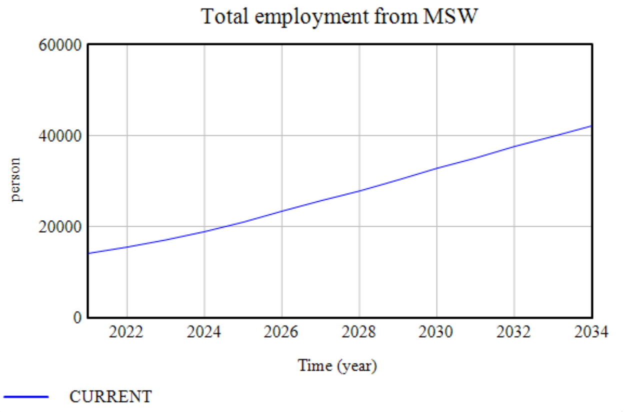
The he Business as Usual (BAU) Scenario is a continuation of current practices without major policy or infrastructure innovations. Efficiency in sorting is poor at 10%, and the rate of recycling is poor at below 10%, limited to small scale and informal activities. The waste is predominantly sent to uncontrolled landfills, and approximately 67% of the total MSW stream ends up in landfills, 32% goes to struggling WTE facility Reppie, and less than 1% is composted. The calorific value remains low since there is no segregation at the source, and energy recovery remains low. This situation results in continuous methane emission due to landfilling, high operating expenses, and loss of potential for resource recovery.


MSW generation
tons/year
3 M
2 M
1 M
0
2022
2024
2026
2028
2030
2032
2034
Time (year)
CURRENT
C:\Users\User\Desktop\extracted SD\waste gen


Selected Variables
tons/year
1.5 M
1 M
500000
0
2022
2024
2026
2028
2030
2032
2034
Time (year)
MSW composting : CURRENT
MSW landfilling : CURRENT
MSW Incinerating : CURRENT
MSW recycled : CURRENT


Selected Variables
tCO2e/year
4 M
2 M
0
2022
2024
2026
2028
2030
2032
2034
Time (year)
emission growth : CURRENT
net GHG from LD : CURRENT
net GHG from MSW COP : CURRENT
net GHG from MSWIN : CURRENT


net cost of MSW treatment
birr/year
4 B
3 B
2 B
1 B
2022
2024
2026
2028
2030
2032
2034
Time (year)
CURRENT


Total employment from MSW
person
60000
40000
20000
0
2022
2024
2026
2028
2030
2032
2034
Time (year)
CURRENT

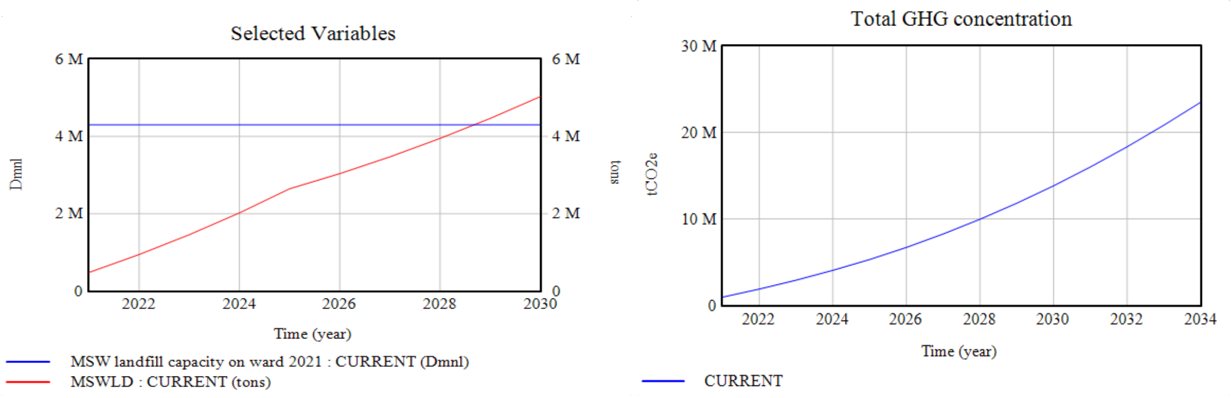


Fig 4.5 Business as Usual (BAU) which is named as CURRENT

Scenario 1: Business as Usual (BAU): In the BAU scenario, the simulation shows that MSWLD (municipal solid waste to landfill) is high, resulting in ongoing methane emission and overall higher level of GHGs. Due to negligible investment on sorting ,composting, employment in the industry is moderate and limited recycling activities. With incineration operating at below full capacity and composting contributing very little, the system remains inefficient and emission intensive. GHG concentration rises over time as a result of compounding from uncontrolled organic waste decomposition and lack of emission mitigation controls.

In the base run, the simulation mimics a steady increasing amount of municipal solid waste sent to landfills (MSWLD), while the total available landfill capacity 0n ward 2021 is kept constant over the course of the simulation. As the graph illustrates, MSWLD surpasses the existing landfill capacity by the year 2028 and a half. This means that, business as usual, Addis Ababa's primary landfill plant will be capacity-constrained within three years from now. This finding indicates the unsustainability of ongoing application of landfilling and highlights the necessity of applying alternative waste treatment technologies such as composting, recycling, and energy recovery to relieve pressure on finite landfill capacity and avoid future urban waste crisis.

The Organic Waste Diversion and Increased Sorting Scenario focuses on the diversion of a large proportion of organic waste to composting. The effectiveness of sorting improves to 40% due to community level source separation schemes, information campaigns, and the use of compost incentives. Capacity of composting is expanded to handle at least 30% of biodegradable waste, while landfilling is reduced to around 35%. The Reppie WTE operates at it's half capacity due to improved quality feedstock, and incremental gains are made in recycling (about 15%) due to material separation efficiencies. This scenario reduces methane emissions significantly, enhances soil health by use of compost, and creates green jobs from low tech treatment facilities.

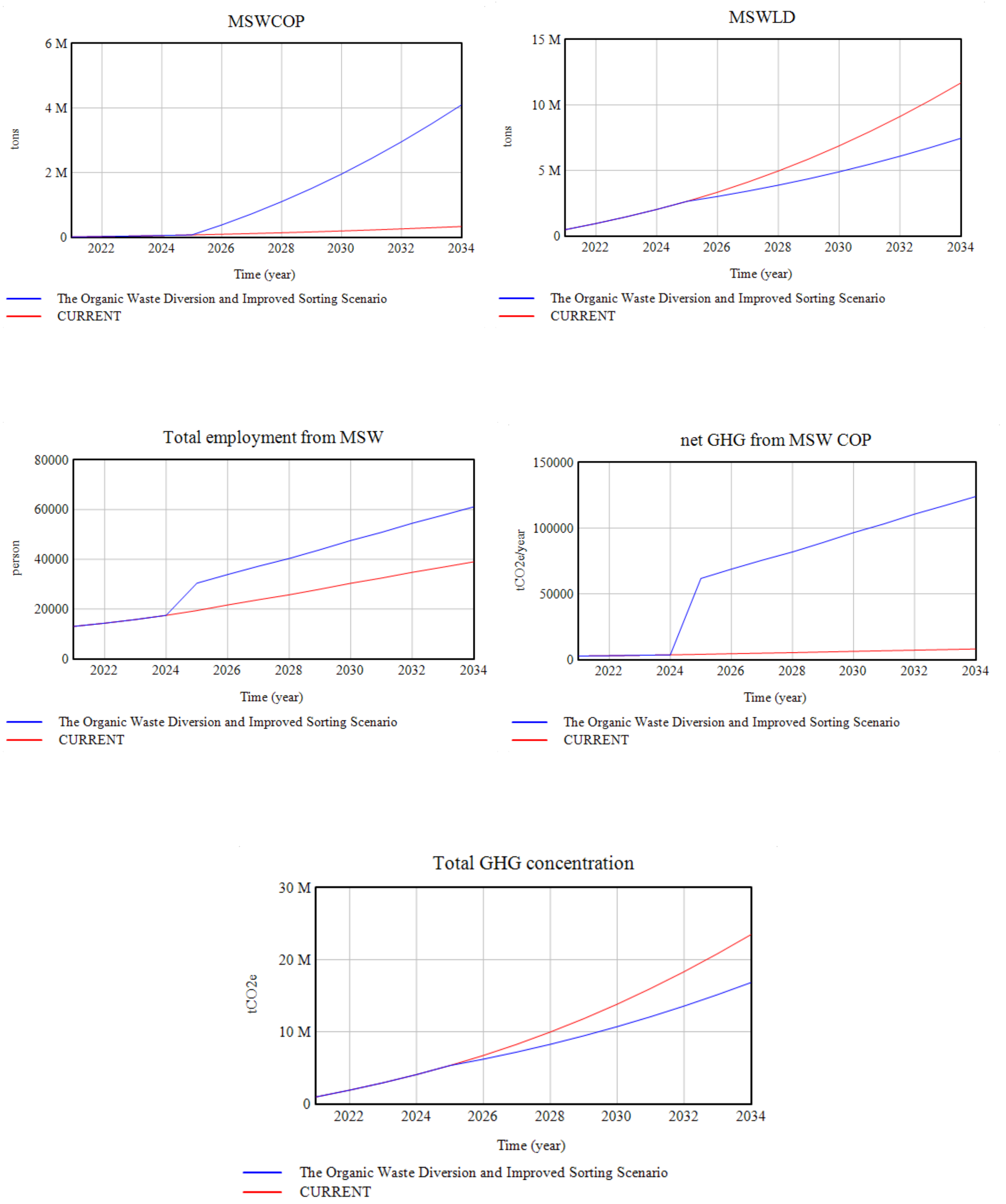
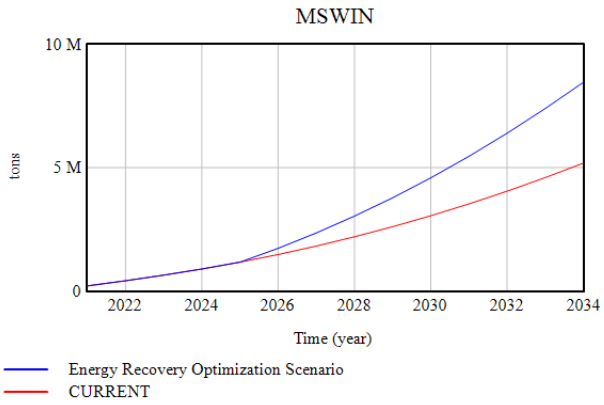
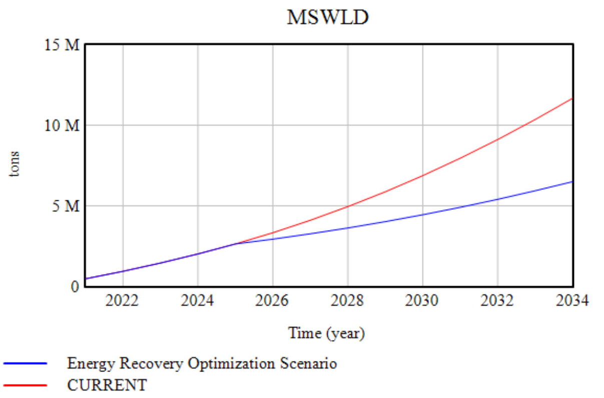


Fig 4.6: Organic Diversion and Improved Sorting scenario and BAU(CURRENT) scenario.

Scenario 2: Organic Diversion and More Sorting: In this scenario, MSWLD is reduced significantly as organic waste is diverted more to composting . Net GHG emissions from composting (COP) increase with more volume processed, but total GHG concentration decreases since composting has a much lower emission factor per ton than landfilling. Labor levels are higher as composting is labor-intensive and needs hand sorting, especially at community and neighborhood scales. Secondly, the system is also environmentally more sustainable because organic waste is recycled constructively and improves soil fertility and reduces landfill dependency.

The third scenario that is Energy Recovery Optimization Scenario emphasizes maximizing electricity production through improved WTE operation. Efficient sorting enhances to 70% in order to upgrade the calorific value of the waste stream to make it possible for the WTE plant to process a higher percentage of MSW up to 60% and reduce the volume of unprocessed waste. Composting remains limited 5% due to the policy focus on combustion based treatment, and recycling remains primitive 10%. Landfilling is also reduced to 30%, with a phased transition towards managed disposal methods. While this scenario is properly reducing landfill methane emissions and increasing energy recovery, it introduces additional carbon dioxide emissions through incineration. It also raises concerns regarding incineration cost, feedstock quality requirements, and long term sustainability.





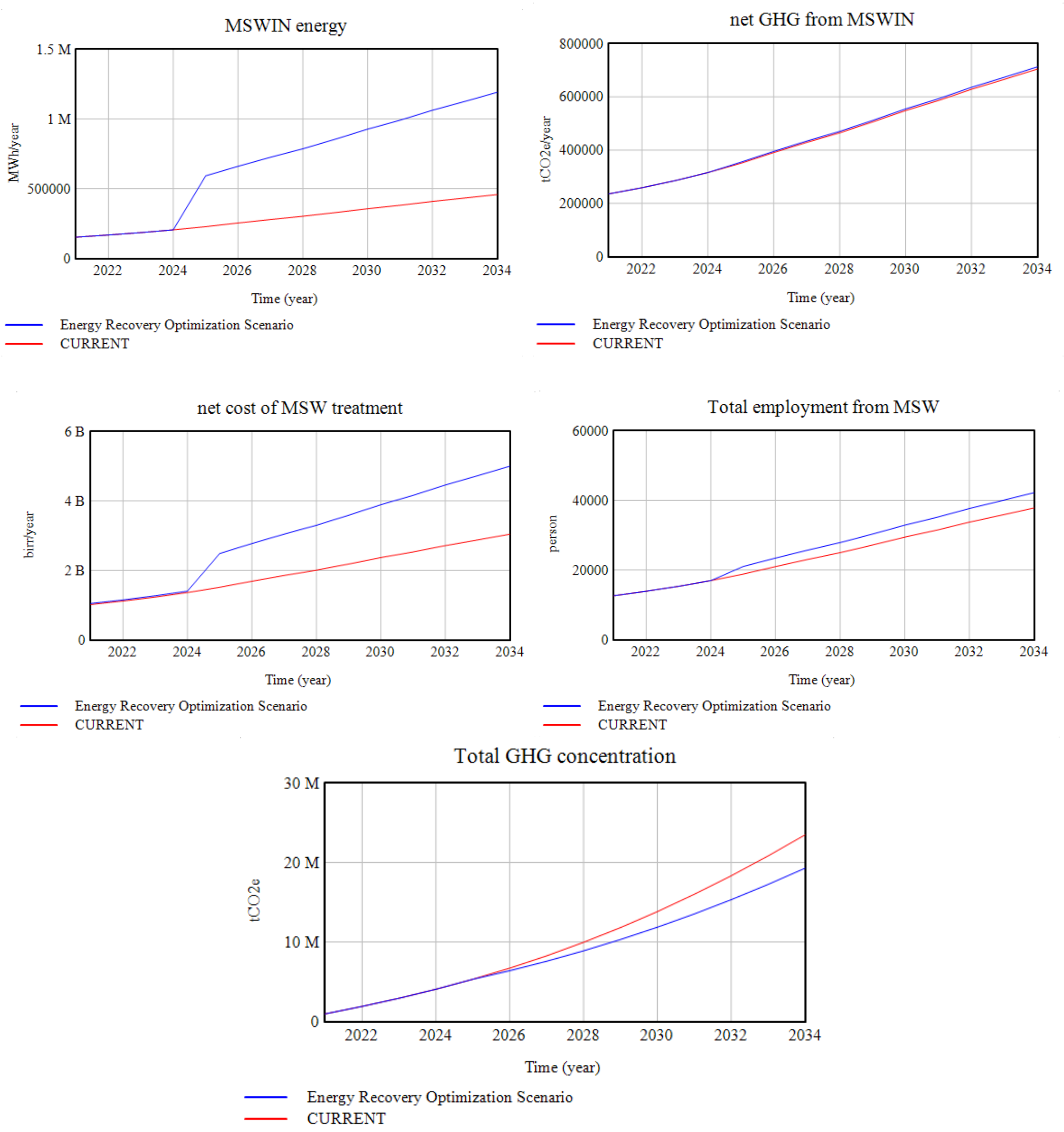
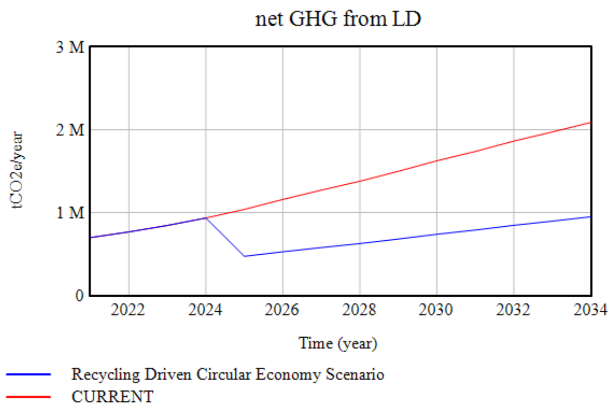
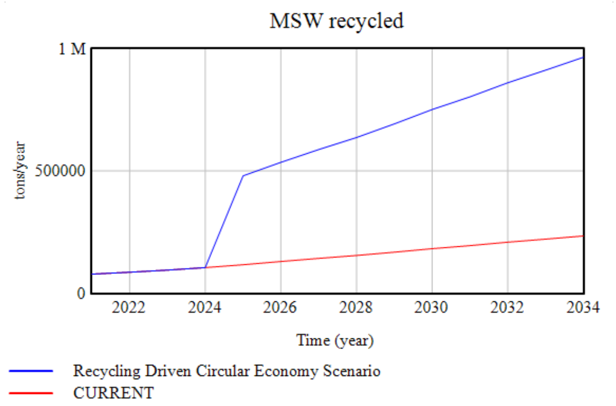


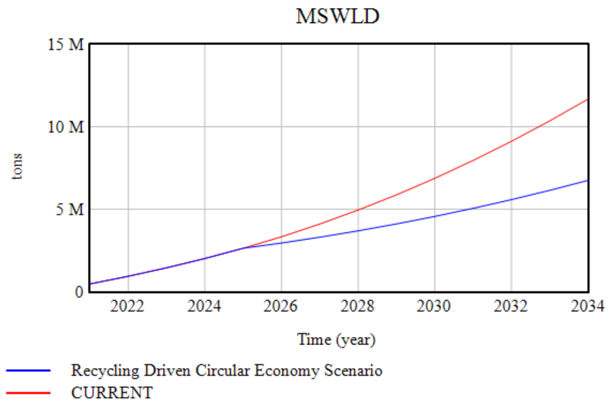
Fig 4.7: Energy Recovery Optimization Scenario and BAU(CURRENT) scenario.

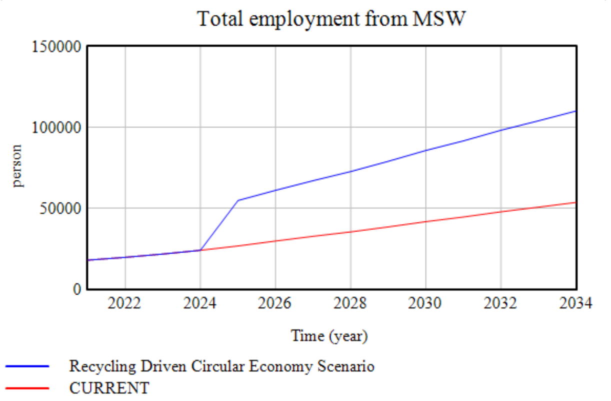
Scenario 3: Energy Recovery Optimization: This scenario made the waste going to landfill plummet with incineration (MSWIN) being the most common treatment practice. The Total GHG emissions had differing results: while methane emissions from landfills reduced, CO_2 emissions from burning increased with the higher volume of waste treated with WTE. Efficiency gains in sorting levels led to higher calorific values, improving the energy output, but system costs and emissions remained higher than with composting led solutions. Employment was raised moderately due to operational improvement, but less spectacularly than with composting or recycling cases, owing to the capital intensive and less labor-intensive nature of WTE technologies.

And the fourth scenario, The Recycling Driven Circular Economy scenario, implements policy interventions to maximize material recovery. Via investments in sorting facilities, buy back stations, and extended producer responsibility (EPR) schemes, recycling rate is 25%. Sorting efficiency is 40%, enabling diversion of more recyclables before treatment. 10% organic waste is handled via composting with decentralized composting systems operational. The remaining waste is split between WTE 30% and landfilling 55%. This condition meets much greenhouse gas emission savings, saves treatment costs through less high capital technology dependence, and supports formal and informal recycling employment generation. It is also conducive to the principles of circular economy through extended product lifecycles and reduced virgin material extraction.









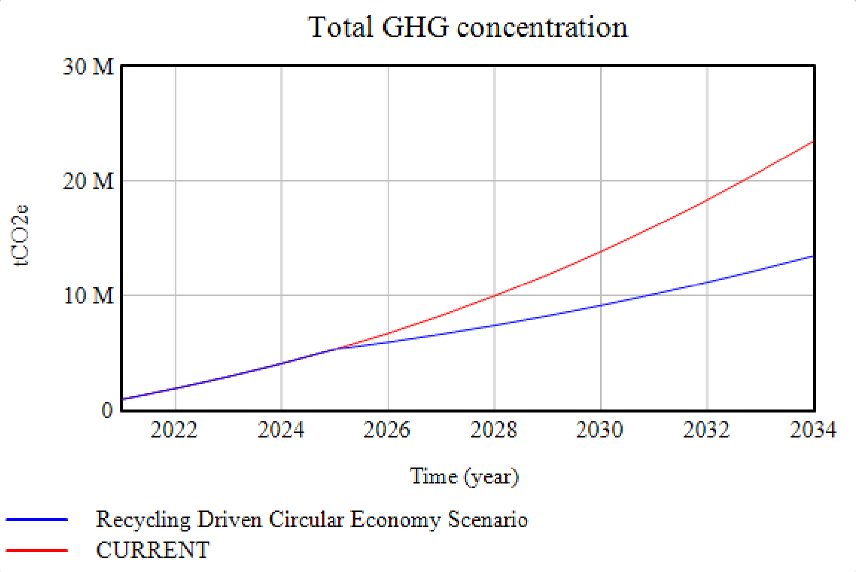
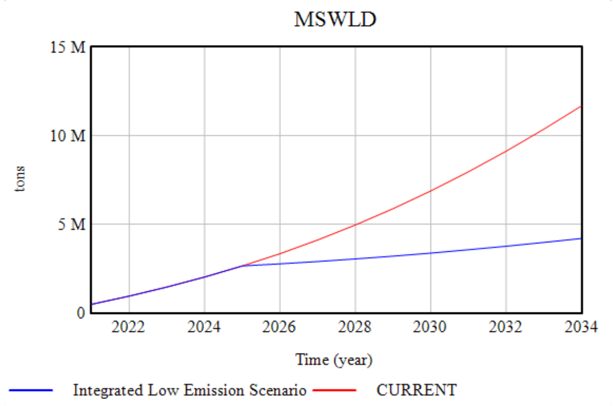
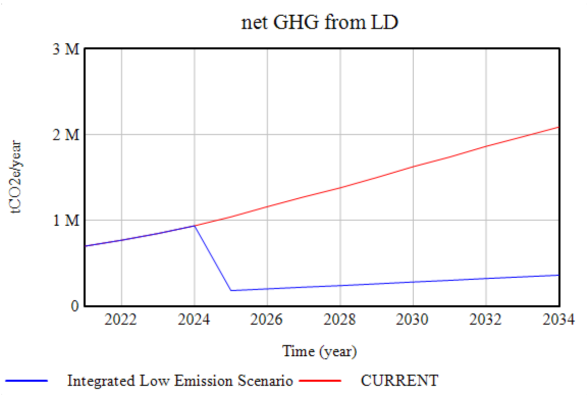


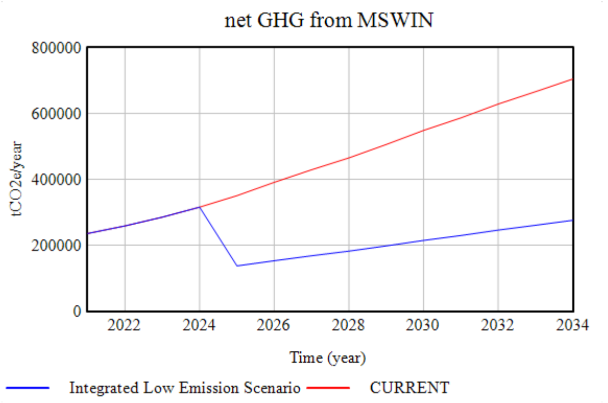
Fig 4.8: Recycling Driven Circular Economy Scenario and BAU(CURRENT)

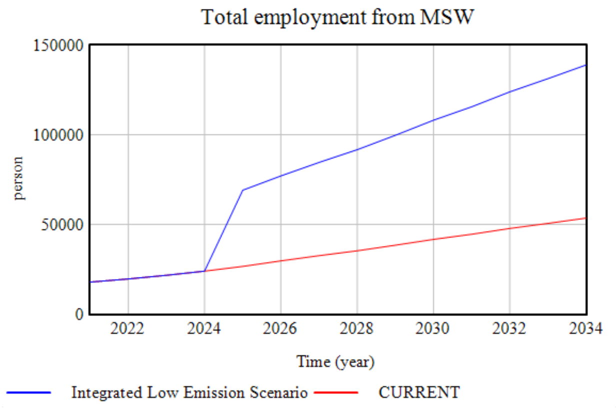
Scenario 4: Recycling Driven Circular Economy: In this scenario, increased recycling infrastructure and more efficient sorting led to a dramatic reduction in both MSWLD as well as incineration emissions.Though recycling itself had a negligible contribution to reducing direct emissions, it made a big difference in reducing the burden on other treatment systems. Total GHG emissions dropped due to the combined effect of landfill reduction and high emission waste streams diversion. Employment growth was robust, particularly in low-income communities, due to the robust demand for waste collection, material recovery, and treatment activities. Such a trend allowed for good environmental as well as economic co benefits, especially in urban jobs creation and resource efficiency. Lastly, the Integrated Low Emission Scenario combines the strengths of the aforementioned models to yield the most climate resilient and economically equitable outcome.

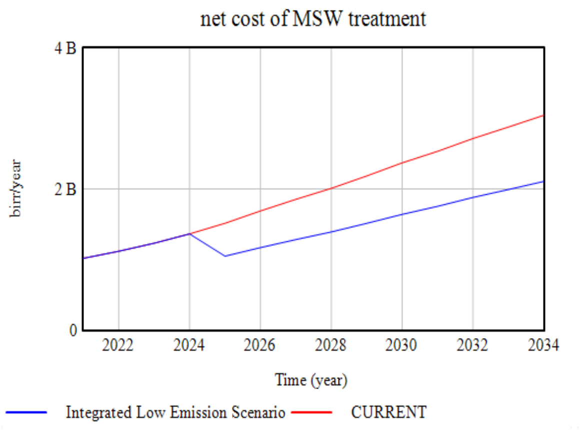
The Fifth scenario which is Integrated Low Emission scenario will be better planned and more balanced in dealing with Addis Ababa's waste. Sorting efficiency is more than 70%, facilitated by widespread public participation and institutional coordination. 25% of recyclables are taken up by recycling, another 30% by composting, and 40% of combustible waste is treated by WTE. A mere 20% of total MSW goes to landfilling. This integrated system has the least net GHG emissions in all cases, achieves the highest economic value recovery in the form of energy and material recovery, and provides the most balanced job benefits for both formal and informal waste streams. It supports Ethiopia's Climate Resilient Green Economy (CRGE) Strategy and offers a replicable model for sustainable waste management in urban areas.

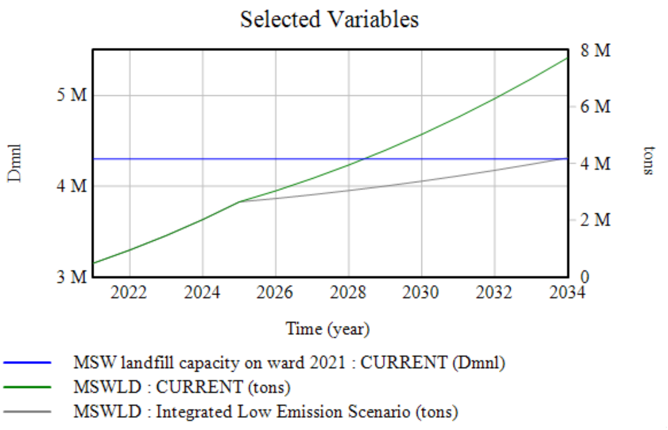












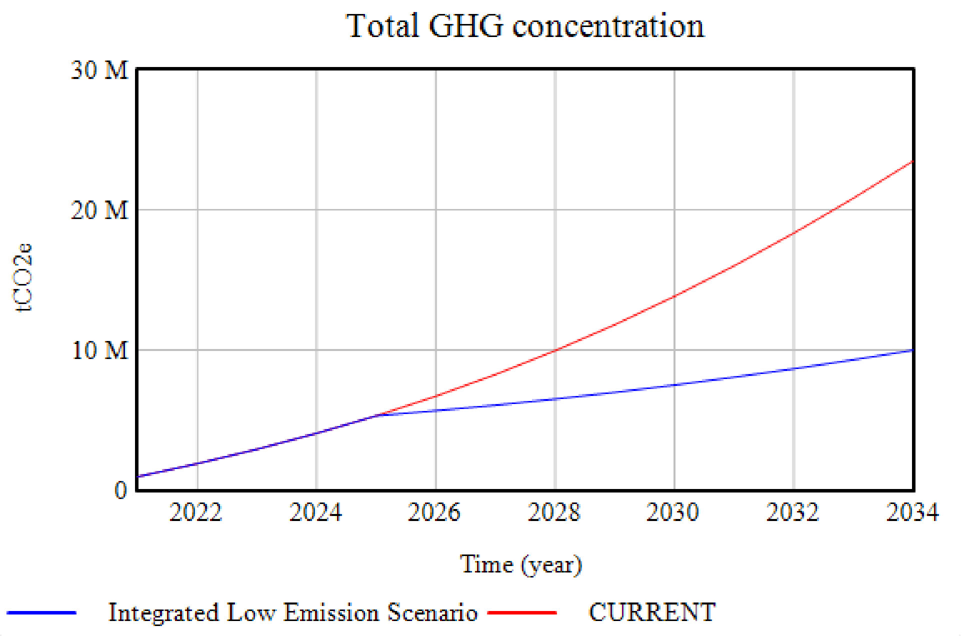


*Fig 4.9: **The Integrated Low Emission scenario and BAU(CURRENT)***

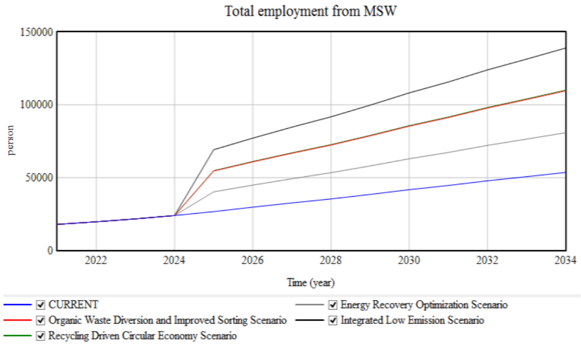
Through the Integrated Low Emission scenario, around 25% of the trash is recycled, 30% is composted, vigorous sorting efforts and 40% of the combustible material is undergoing treatment through the Reppie waste to energy plant. This means that only part of 15% of overall municipal waste ends up in landfill. These initiatives bring about a sharp decrease in greenhouse gas emissions, especially methane from organic waste. The sector as a whole emits less than 10 million tons of CO_2 equivalent by the year 2034 which is, less than half of what would be emitted when having business as usual. Besides this, employment in the waste sector goes up by a significant number, driven by the work demands of composting, recycling, and decentralized waste collection. As most of the waste is being redirected away from landfill, Koshe's burden is relieved by quite a bit.

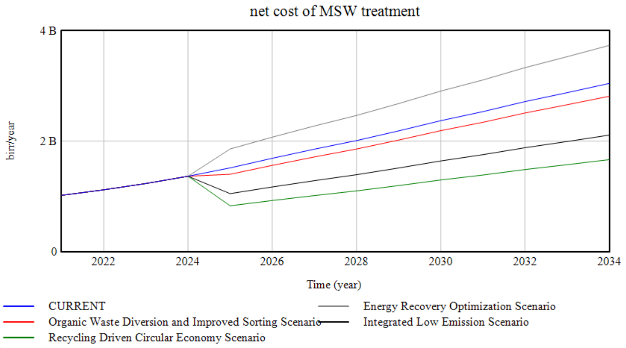
The total landfill capacity ahead of 2021 was around 4 to 4.3 million tons. Under the baseline scenario, that peak capacity would be achieved in 2028 and create extreme overflow waste problems. But under the Integrated scenario, landfill utilization rises far more slowly, and the landfill won't fill up until around 2034. That gives the city six extra years to plan and ready a new site for a landfill or expand other treatment capacity without precipitating a crisis and buying valuable time. In addition to lowering emissions and landfill life, the combined scenario also provides strong economic and social benefits.

In addition to cutting emissions and extending landfill life, the integrated scenario also brings strong economic and social benefits. It creates thousands of new jobs across the recycling and composting sectors, supports energy generation through WtE, and reduces long term costs by limiting the need for emergency dumping or rapid infrastructure expansion. Altogether, it offers a clear, practical path toward a cleaner, more sustainable city one that supports the goals of Ethiopia's Climate Resilient Green Economy strategy while improving daily life for its residents.

4.4. Scenario Analysis

The model simulated critical parameters of waste management for different policy scenarios. Results of these scenarios are shown in figures presented below. Under the Business as Usual (BAU) scenario, there was low sortation and minimal investment in recycling or composting, leading to intensive landfill use and constant greenhouse gas (GHG) emissions. The landfill is saturated in 2028, and overall sector emissions accelerate with time. The Improved Sorting and Composting scenario, Energy Recovery Optimization (WtE Focused), The Energy Recovery Optimization (WtE Focused) and The Recycling Driven Circular Economy scenario had low organic waste to landfill reduction and somewhat longer landfill lifetime, but emissions were relatively high. On the other hand, the Integrated Low Emission scenario, with optimized sorting, material recovery, composting, and efficient waste to energy use, resulted in the least GHG emissions and longest landfill lifespan, up to around 2034 capacity. The scenario also produced most employment and was most consistent with climate and sustainability goals.





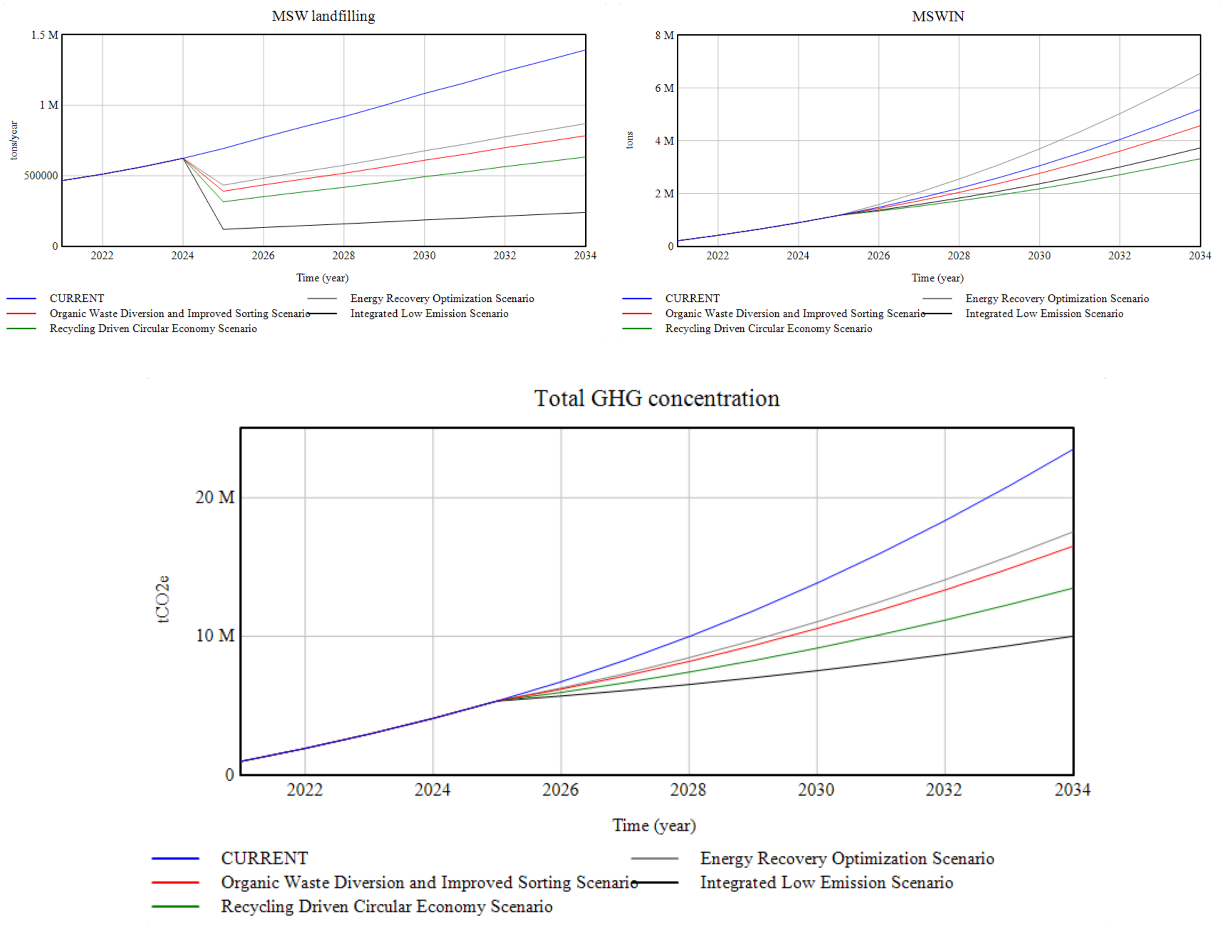


Fig 4.10: Different variables under Different Scenarios

The Composting and Sorting Improvement scenario, greater diversion of organic waste to composting reduced landfill pressure moderately and reduced methane emissions slightly. Labour supply increased due to the labour intensive nature of composting, but investment in recycling and energy recovery technologies was constrained, which plateaued both emissions reduction and revenue growth. In the Energy Recovery Optimization scenario, measures focused on maximizing the use of the Reppie waste to energy plant. This path reduced landfill bound waste and methane emissions considerably but incineration CO_2 emissions remained considerable. Furthermore, this scenario was the most expensive in absolute terms, even surpassing the BAU case on net cost, due to the substantial costs of incineration plant capital and operation costs. The employment benefits were also low, as WtE technologies are often capital more than labor intensive.

The Integrated Low Emission scenario generated the most balanced and sustainable results. By 25% recycling, 30% composting, and 40% waste to energy treatment along with enhanced sorting, it reduced the level of waste to landfills to as little as 15% advancing the life of the landfill to about 2034. So this scenario created the lowest greenhouse gas emissions, tripled jobs in the waste sector through labor intensive processes like recycling and composting, and offered a superior long term economic opportunity. Although it involved higher initial investment, its overall expense was lower in the long term through savings in emissions, energy recovery, and improved material use. It is also the most climate resilient and economically inclusive choice and comes close to Ethiopia's Climate Resilient Green Economy (CRGE) strategy.

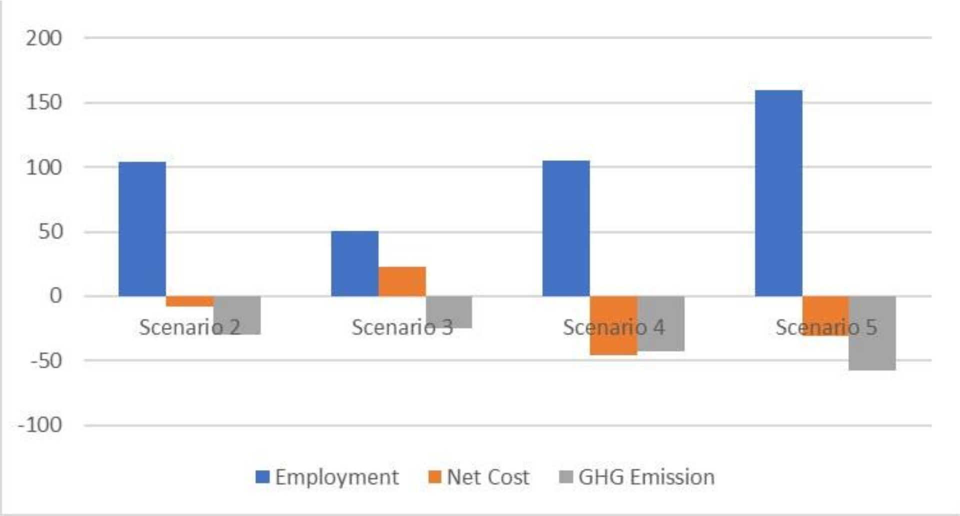


Fig 4.11Comparative Impact of Policy Scenarios on Employment, Cost, and Emissions in 2034

This graph illustrates the percentage change in employment, net cost, and GHG emissions under four alternative waste management scenarios (Scenarios 2–5), compared to the Business as Usual (Scenario 1) at the end of the simulation period which is 2034. Scenario 5 (Integrated Low Emission) shows the best overall performance, with the highest employment growth, the greatest reduction in emissions, and a notable cost saving. Scenario 4 as well performs well in all three areas. Scenario 2 is good for job creation with moderate environmental benefits, while Scenario 3, focuses on energy recovery, reduces emissions roughly but results in the highest net cost increment, making it the least cost effective option.

Chapter Five

5. Conclusion and Policy Implications

5.1. Conclusion

The study developed a system dynamics model to examine the Addis Ababa MSW management system under different policy paths during 2021 to 2034. It aimed to examine the long term implications of waste management decisions on greenhouse gas (GHG) emissions, jobs creation, net system spending, and landfill space utilization. Five scenarios were tested: Business as Usual (BAU), Improvement in Composting and Sorting, Energy Recovery Maximization, Recycling Driven Circular Economy and the Integrated Low Emission scenario.

Results from Business as Usual scenario projected that Addis Ababa's major disposal site Koshe landfill will be capacitated by 2028 by rising amounts of waste and absence of diversion measures. This presents an acute threat to the sanitation infrastructure and the environmental safety of the city. GHG emissions here continue to increase steadily, waste industry employment continues to be low, and long-term system costs are no longer sustainable because of increasing environmental and operational burdens. The Composting and Sorting scenario and Recycling Driven Circular Economy Scenario increased landfill diversion moderately and job creation moderately and reduced the GHG emission moderately too. The Energy Recovery scenario, which most maximized the Reppie waste to energy (WTE) plant, reduced methane emissions due to landfilling but was the most expensive net among all scenarios. It also generated proportionately minimal employment, as WTE production is capital rather than labor intensive.

The Integrated Low Emission scenario was the best performer and balanced. With more than 70% effectiveness of sorting and planned diversion strategy 25% of the waste directed for recycling, 30% for composting, and 40% merely for energy recovery alone 20% of the overall waste was ultimately landfilled. This seriously alleviated pressure on the Koshe landfill and its lifespan extended to 2034, giving the city a much-needed six year period within which to complete the new Sendafa sanitary landfill project currently under construction northeast of Addis Ababa. This scenario also produced the lowest GHG emissions, tripled employment in the waste sector, and reduced long term system costs, giving the optimal match with Addis Ababa's green growth and urban resilience goals. Additionally, although the Reppie WTE plant has the capacity to produce 185 GWh of electricity per annum through the processing of 1,400 tons of waste daily, it still faces some serious operation challenges including unreliable feedstock, neglected maintenance, and unclear institutional coordination. These realities make the Integrated scenario in place of dependence on WTE a safer and more robust path towards sustainable waste management.

5.2. Policy Implications

The findings of this study point to the need for Addis Ababa to shift to an integrated and climate-responsive solid waste management system. Governments should channel efforts into large-scale composting, recycling, and source separation programs to reduce dependency on landfilling. As Koshe landfill is expected to fill up by 2028, the city has a pressing need to accelerate the construction and start-up of the new Sendafa landfill site and equip it with sound environmental protection mechanisms and leachate management systems. This six year buffer, realized through the Integrated Low Emission scenario, must be optimized to avoid precipitating a waste overflow crisis.

Also, the city must stabilize and optimize the Reppie WTE plant. Though the infrastructure has been in operation since 2018, erractic performance as a result of mechanical problems and lack of coordination among stakeholders has made it less reliable. Constant maintenance, feedstock preparation, as well as having a well-defined institutional management hierarchy, is essential to realizing its full potential. Besides this, Bole Arabsa recycling plant, planned decentralized composting sites, and Material Recovery Facilities (MRFs) proposed in other sub cities should be expedited and made operational at the earliest. These plants are imperative in order to keep organic and recyclable wastes away from landfills, and also offer significant employment generation opportunities. Moreover, there is a necessity for building strong informal sector partnerships on which material recovery is largely dependent and increasing public engagement and participation in sorting, since these are essential elements towards long term success of the system.

5.3. Limitations and Future Research

The research limitations include simulation of the Addis Ababa waste management system at an aggregated level. It does not reflect spatial disparities between sub cities or intra period variability in waste generation behavior by income group or season. The model also presumes complete policy implementation and system effectiveness, which can be subject to failure under real world conditions such as delays in funding, political change, or inadequate enforcement. In addition, although institutional and social factors are recognized, they are not quantitatively represented, which can underestimate implementation difficulties.

Bringing in the informal waste sector involves further consideration of decentralised waste treatment systems, including neighbourhood scale composting and local recycling facilities, and how these overlap or compete with central waste streams. More detailed studies of the economic viability of bringing in the informal waste sector are also necessary, in order to explore income generation, conditions of employment, and social protection. Additional research is also recommended to establish the overall lifecycle emissions of different alternatives of waste treatment, particularly the long term performance of WTE for low calorific waste streams. Finally, additional field based research is needed to monitor the progress and potential of the Sendafa landfill project, i.e., cost control, quality of construction, and social and environmental management plans, to ensure it is capable of meeting the future requirements of the city.

Under the Business as Usual scenario, results revealed that Addis Ababa's main disposal site Koshe landfill will reach its full capacity by 2028, driven by rising waste volumes and limited diversion interventions. This presents a serious risk to the city's sanitation infrastructure and environmental safety. GHG emissions in this scenario continue to rise steadily, employment in the waste sector remains minimal, and long term system costs become unsustainable due to increasing environmental and operational pressures. The Composting and Sorting scenario and Recycling Driven Circular Economy Scenario moderately improved landfill diversion and employment creation and reduced the GHG emission moderately also. The Energy Recovery scenario, which focused on maximizing the Reppie waste to energy (WTE) facility, reduced methane emissions from landfilling but incurred the highest net cost among all scenarios. It also generated relatively low employment, as WTE operations are capital rather than labor intensive.

The most effective and balanced option was the Integrated Low Emission scenario. With more than 70% sorting efficiency and a structured diversion strategy 25% of waste directed to recycling, 30% to composting, and 40% to energy recovery only 20% of total waste was landfilled. This significantly relieved pressure on the Koshe landfill and extended its lifespan to 2034, giving the city a crucial six year window to complete the new Sendafa sanitary landfill project, currently under construction northeast of Addis Ababa. This scenario also led to the lowest GHG emissions, tripled employment in the waste sector, and reduced long term system costs, offering the best alignment with Addis Ababa's green growth and urban resilience priorities. Additionally, while the Reppie WTE plant has the potential to contribute up to 185 GWh of electricity annually by processing 1,400 tons of waste per day, it continues to face major operational challenges including inconsistent feedstock, maintenance delays, and unclear institutional coordination. These realities make the Integrated scenario rather than overreliance on WTE a safer and more adaptive pathway for sustainable waste management

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Appendix

Model equations, values and units

(01) Annual MSW generation per capita= Normal annual MSW generation per capita*waste generation factor

Units: tons/(year*person)

(02) AP COP= (proportion for COP/ratio sum)+(0.1*Sorting efficiency)

Units: Dmnl [0,1]

(03) AP INC= proportion for IN/ratio sum

Units: Dmnl [0,1]

(04) AP LD= (proportion for LD/ratio sum)-(0.1*Sorting efficiency)

Units: Dmnl

(05) Calorific level=(4930+(9000-4930)*Sorting efficiency)*unit change 2

Units: KJ/KG

(06) Calorific level in KJ= Calorific level*Unit change

Units: KJ/tons

(07) cost for MSWIN per ton=4903

Units: birr/tons

(08) cost of MSW collection per ton=23

Units: birr/tons

(09) cost of MSW recycling per ton=234

Units: birr/tons

(10) electricity price=723.2

Units: birr/MWh

(11) emission growth=net GHG from MSW COP+net GHG from LD+net GHG from MSWIN

Units: tCO2e/year

(12) employment per birr invested=0.00035

Units: person/birr

(13) FINAL TIME = 2034

Units: year

The final time for the simulation.

(14) GDP= INTEG (GDP growth,1.3909e+12)

Units: birr

(15) GDP growth=GDP*GDP growth rate

Units: birr/year

(16) GDP growth rate= 0.18

Units: 1/year

(17) IN residuals=MSW Incinerating*residuals for IN per ton

Units: tons/year

(18) income from fertilizer per ton= 3000

Units: birr/tons

(19) income from MSWIN energy= MSWIN energy*electricity price

Units: birr/year

(20) income from produced fertilizer= income from fertilizer per ton*produced frtilizer

Units: birr/year

(21) INITIAL TIME = 2021

Units: year

The initial time for the simulation.

(22) Investment for MSW= (Investment for MSW LD+Investment for MSWIN+investment MSW COP+Investment for MSW collection+Investment for MSW recycling)*unit change 3

Units: birr

(23) Investment for MSW collection= cost of MSW collection per ton*MSW col

Units: birr/year

(24) Investment for MSW LD=MSW landfilling*Investment for MSW LD per ton

Units: birr/year

(25) Investment for MSW LD per ton= 218

Units: birr/tons

(26) Investment for MSW recycling= MSW recycled*cost of MSW recycling per ton

Units: birr/year

(27) Investment for MSWIN= MSW Incinerating*cost for MSWIN per ton

Units: birr/year

(28) investment MSW COP= MSW composting*(investment MSW COP per ton)

Units: birr/year

(29) investment MSW COP per ton=4000

Units: birr/tons

(30) migration rate= 0.016

Units: 1/year

(31) MSW col=MSW generation*rate MSW col

Units: tons/year

(32) MSW composting= AP COP*MSW TR

units: tons/year

(33) MSW generation=Annual MSW generation per capita*Population

Units: tons/year

(34) MSW Incinerating= AP INC*MSW TR

Units: tons/year

(35) MSW landfill capacity on ward 2021= 4.3e+06

Units: Dmnl

(36) MSW landfilling=AP LD*MSW TR+IN residuals

Units: tons/year

(37) MSW recycled= MSW col*rate of MSW recycling*Sorting efficency effect on recycling

Units: tons/year

(38) MSW TR=MSW col*rate of MSW TR-(MSW recycled*(Sorting efficency effect on recycling -1))

Units: tons/year

(39) MSWCOP= INTEG (MSW composting, 7178.04)

Units: tons

(40) MSWIN= INTEG (MSW Incinerating, 210773)

Units: tons

(41) MSWIN energy= MSW Incinerating*MSWIN energy per ton

Units: MWh/year

(42) MSWIN energy per ton= Scale parameter 2*(Calorific level in KJ)/7.2e+06

Units: MWh/tons

(43) MSWLD= INTEG (MSW landfilling, 480968)

Units: tons

(44) net cost of MSW COP= investment MSW COP-income from produced fertilizer

Units: birr/year

(45) net cost of MSW LD= Investment for MSW LD*1

Units: birr/year

(46) net cost of MSW treatment=net cost of MSW COP+net cost of MSW LD+net cost of MSWIN

Units: birr/year

(47) net cost of MSWIN= Investment for MSWIN-income from MSWIN energy

Units: birr/year

(48) net GHG from LD=MSW landfilling*unt net GHG from LD

Units: tCO2e/year

(49) net GHG from MSW COP=MSW composting*unit net GHG emission fro COP

Units: tCO2e/year

(50) net GHG from MSWIN= unit net GHG from IN*MSW Incinerating

Units: tCO2e/year

(51) Normal annual MSW generation per capita= 0.16786

Units: tons/(year*person) [0,?]

(52) per capita income= GDP/Population

Units: birr/person

(53) Popn increament= Population*rate of popn growth

Units: person/year

(54) Population= INTEG (Popn increament,5.006e+06)

Units: person

(55) produced frtilizer=1*MSW composting

Units: tons/year

(56) proportion for COP=0.011

Units: Dmnl [0,1]

(57) proportion for IN= 0.323

Units: Dmnl [0,1]

(58) proportion for LD= 1-proportion for COP-proportion for IN

Units: Dmnl [0,1]

(59) Proportion of MSWTR INV to GDP=Investment for MSW/GDP

Units: Dmnl

(60) rate MSW col= 0.85

Units: Dmnl [0,1]

(61) rate of MSW recycling= 0.099

Units: Dmnl [0,1]

(62) rate of MSW TR=1-rate of MSW recycling

Units: Dmnl [0,1]

(63) rate of natural growth= 0.02668

Units: 1/year

(64) rate of popn growth= rate of natural growth+migration rate

Units: 1/year

(65) ratio sum= proportion for COP+proportion for IN+proportion for LD

Units: Dmnl [0,1]

(66) reference income=272725

Units: birr/person

(67) relative income= per capita income/reference income

Units: Dmnl

(68) residuals for IN per ton= 0.22

Units: Dmnl

(69) SAVEPER = TIME STEP

Units: year [0,?]The frequency with which output is stored.

(70) scale parameter=1

Units: tCO2e/KJ

(71) Scale parameter 2= 1

Units: MWh/KJ

(72) Sorting efficency effect on recycling= 1+Sorting efficiency

Units: Dmnl

(73) Sorting efficiency=0.1

Units: Dmnl [0,1]

(74) TIME STEP = 1

Units: year [0,?] The time step for the simulation.

(75) Total employment from MSW= employment per birr invested*(Investment for MSW collection*0.07+Investment for MSW LD *0.07+Investment for MSW recycling*1+Investment for MSWIN*0.02+investment MSW COP*0.08)*unit change 3

Units: person

(76) Total GHG concentration= INTEG (emission growth, 963143)

Units: tCO2e

(77) Unit change= 1000

Units: KG/tons

(78) unit change 2=1

Units: KJ/KG

(79) unit change 3=1.03

Units: year

(80) unit net GHG emission fro COP= 0.2

Units: tCO2e/tons

(81) unit net GHG from IN= (2.1-1.8e-07*Calorific level in KJ)*scale parameter

Units: tCO2e/tons

(82) unt net GHG from LD= 1.5

Units: tCO2e/tons

(83)waste generation factor = WITH LOOKUP (relative income, ([(0,0)-(5,2)],(0.2,0.5),(0.5,0.8),(1,1),(2,1.4),(3,1.6),(4,1.7),(5,1.75)))

Units: Dmnl