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Environmental Life Cycle Impact Assessment of Waste to Energy System: The Case for Bahir Dar City

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BAHIR DAR INSTITUTE OF TECHNOLOGY

SCHOOL OF RESEARCH AND GRADUATE STUDIES

FACULTY OF CHEMICAL AND FOOD ENGINEERING

MASTER IN ENVIRONMENTAL ENGINEERING

MSc. THESIS ON:

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By:

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March, 2024

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Fanuel Bayeh

A Thesis Submitted to the School of Research and Graduate Studies of Bahir Dar Institute of Technology in Partial Fulfillment of the Requirements of the Degree of Masters of Science in Environmental Engineering, in the Faculty of Chemical and Food Engineering.

Advisor: Eshetu Getahun (PhD)

March, 2024

Bahir Dar, Ethiopia

DECLARATION

DECLARATION

This is to certify that the thesis entitled **"Environmental life cycle impact assessment of waste to energy system: The Case for Bahir Dar Town"**, submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental Engineering under Faculty of Chemical and Food Engineering, Bahir Dar Institute of Technology , is a record of original work carried out by me and has never been submitted to this or any other institution to get any other degree or certificates. The assistance and help I received during the course of this investigation have been duly acknowledged.

Name of the student:	Signature	Date
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Approval of thesis for defense

I hereby certify that I have supervised, read, and evaluated this thesis titled **Environmental Life Cycle Impact Assessment of Waste to Energy System: The Case for Bahir Dar Town** prepared by Fanuel Bayeh under my guidance. I recommend the thesis to be submitted for oral defense.

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Advisor ‘s name Signature Date

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APPROVAL OF THESIS FOR DEFENCE RESULT

I hereby confirm that the changes required by the examiners have been carried out and incorporated into the final thesis.

Name of the Student: Fanuel Bayeh Signature_____ Date 12/04/2024

As members of board of examiners, we examined this thesis entitled **"Environmental Life Cycle Impact Assessment of Waste to Energy System: The Case for Bahir Dar City"** by Fanuel Bayeh. We hereby certify that the thesis is accepted for fulfilling the requirements for the award for the degree of master of science in "Environmental Engineering".

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LIST OF ABBREVATIONS

AP………………………………………… Acidification potential

CML…………………………………………Center of Environmental science Leiden

CTUe………………………………………Characterization Factor for Terrestrial Environment

EU………………………………………… European Union

EPA………………………………………… Environmental Protection Agency

EP…………………………………………… Eutrophication Potential

GHG………………………………………… Green House Gas

GWP………………………………………… Global Warming Potential

Kg CO2 eq…………………………………. kilogram carbon dioxide equivalent

Kg PO4 eq……………………………………kilogram phosphate equivalent

Kg SO2 eq…………………………………… Kilogram sulfate equivalent

KWh…………………………………………...Kilowatt-hour

ISWM………………………………………… Integrated Solid Waste Management

LCA………………………………………… Life Cycle Assessment

LHV…………………………………………...Lower Heating Value

LFG………………………………………… Landfill Gas

MC…………………………………………… Moisture Content

MSW………………………………………… Municipal Solid Waste

SWM………………………………………… Solid Waste Management

WTE………………………………………… Waste to Energy

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ABSTRACT

Implementing waste-to-energy systems is an important step toward managing solid waste while generating electricity. However, the implementation of these systems in Bahir Dar town could have several environmental impacts and prospects. The generation of electricity from municipal solid waste needs to be studied carefully to ensure that the benefits outweigh any potential negative effects. The purpose of this research is to conduct a comprehensive environmental life cycle study of different waste-to-energy scenarios for Bahir Dar city, primarily using LCA as an analytical tool. Three waste-to-energy options were evaluated in this study, namely incineration, anaerobic digestion, and landfill gas systems. The study utilized Open LCA software and employed both CML (Center of Environmental Science Leiden) and TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) methodologies to examine the environmental impacts of waste-to-energy systems. The investigated waste-to-energy system is assessed for global warming potential, eutrophication potential, acidification potential, ozone depletion potential, fossil fuel depletion, and ecotoxicity potential. The following results show the environmental impact of three different waste-to-energy systems: incineration, landfill gas systems, and anaerobic digestion. The highest value of fossil fuel depletion (measured in MJ) was found in incineration, using the CML method. The highest ecotoxicity potential (measured in CTUe) was found in incineration, using the TRACI method. The lowest value of fossil fuel depletion was found in anaerobic digestion with the TRACI method, while the lowest ecotoxicity value was found in anaerobic digestion using the CML method. The highest values of acidification potential (measured in kg SO2 eq) and ozone depletion potential (measured in kg CFC-11 eq) were both found in incineration using the TRACI impact assessment method. The lowest value of acidification potential was found in landfill gas systems using the TRACI method, while the lowest ozone depletion potential was found in anaerobic digestion using the CML method. The highest values of eutrophication potential (measured in kg PO4 eq) and global warming potential (measured in kg CO2 eq) were both found in anaerobic digestion using the CML impact assessment method. The lowest values of eutrophication potential and global warming potential were both found in landfill gas systems using the TRACI impact assessment method. Overall, incineration had the highest environmental impact, while landfill gas systems had the lowest environmental impact out of the three waste-to-energy systems.

1. INTRODUCTION

The population all over the world is expanding, connected with that, safeguarding general wellbeing of the ecosystem and the environment becomes critical issue [1]. The rapid urbanization, economic growth, and population increase have led to a significant amount of waste, which has attracted international attention due to its environmental impact [2]. In the last part of the 1960s and mid 1970s numerous researchers and masterminds saw that nonstop population and economic was causing natural decay, and contended that it could not continue to sustain incessantly (Beder, 2006). Waste generation is a characteristic result of urbanization, financial turn of events, and population growth. As countries and urban communities become more populated and prosperous, offer more items and administrations to residents, and take part in worldwide exchange and trade, they face comparing measures of waste to oversee through treatment and removal [3]. Driven by quick urbanization and population growth, worldwide yearly municipal waste generation is supposed to leap to 3.4 billion tons throughout the following 30 years, up from 2.1 billion tons in 2016. However according to United Nations Environmental program, the total solid waste generated per year could be much higher than the specified number. To address this issue, a comprehensive and careful waste management approach is necessary. Municipal Solid Waste Management (MSWM) is the term for the procedures used to collect, move, treat, recycle, recover resources from waste, and dispose of solid waste produced in metropolitan areas. MSWM is a significant duty of local governments and a complicated service requiring the participation of many stakeholders in the public and commercial sectors as well as the necessary organizational, technical, and administrative competence. Waste management is a value chain that involves the collection, treatment, reuse, disposal, and recycling of various waste streams. Given the right conditions, the private sector can invest in waste management activities and benefit economically, making it a more effective partner in environmental management. The management of municipal solid waste is high in more prosperous cities. The majority of developed nations generate between 0.8 and 1.4 kg of garbage per person per day on average, and they effectively manage it. In contrast, the typical generation rate in developing nations is more likely to be between 0.3 and 0.5 kg per person per day, but the methods for processing and managing solid waste have been insufficient and continue to be so [4]. The rate of urbanization in emerging nations is currently astounding, with Africa having an urbanization rate of 3.5% annually. This is higher than the rates in industrialized countries, which are 0.5 and 0.6%, respectively [5]. Ethiopia has the greatest predicted urbanization rate among the majority of emerging nations at about 5.54%, despite the fact that urban environment management is currently a major issue. Ethiopia has struggled to address the issue of proper solid waste management. Municipalities in the majority of Ethiopian cities have experienced significant difficulties with municipal solid waste collection, transportation, and disposal due to the current rate of urbanization [6]. To address these challenges, waste-to-energy (WTE) technologies have gained attention as a potential solution for managing MSW and contributing to the transition towards a more sustainable energy system [7].

WTE technologies involve converting waste into useful forms of energy, such as electricity or heat, through a variety of processes such as combustion, gasification, and digestion [8]. The benefits of WTE include reducing the amount of waste sent to landfills, generating renewable energy, and potentially reducing greenhouse gas emissions[9]. However, WTE also poses challenges such as emissions of pollutants such as particulate matter, nitrogen oxides, and dioxins, which can have negative impacts on air quality and human health [10].

1.2 Problem of statement

Solid waste management is a significant issue in developing regions, particularly in some parts of Africa, where it is considered a sanitation problem. In countries with an effective waste management system, sanitation mainly refers to wastewater and human excreta rather than solid waste. This is because unmanaged solid waste can create health hazards if burned or deposited in rivers and other areas. One of the challenges faced by Ethiopian cities, such as Bahir Dar, is the issue of sanitation, mainly due to a lack of solid waste management. Bahir Dar is a well-known city in Ethiopia, and it is a hub for business and industrial activity. Furthermore, the city's daily waste generation rate is on the rise. While most countries have made significant progress in developing waste-to-energy technology, Ethiopia, in general, and Bahr Dar, in particular, have not yet realized their full potential in this area due to a lack of scientific data to support the application of such technologies. However, some researchers have studied the potential of municipal solid waste (MSW) for energy generation in some parts of Ethiopia. Unfortunately, no Environmental Impact Assessment (EIA) has been conducted to determine the potential environmental impacts of generating energy from municipal solid waste (MSW). There is currently no available information on how the conversion of municipal solid waste to energy may impact Bahir Dar city due to various emissions. This study assesses the life cycle environmental impacts of waste-to-energy systems, such as incineration, anaerobic digestion, and landfill gas systems.

1.3 Objectives

1.3.1 General Objective

The general objective of this study is to evaluate the impact of waste-to-energy methods, such as landfill gas, incineration, and anaerobic digestion, on energy generation in Bahir Dar while considering their ecological repercussions.

1.3.2 Specific Objective

- evaluating the composition of Municipal Solid Waste (MSW) at the waste collection site in Bahir Dar City,
- characterizing the MSW collected from different sites,
- modeling the environmental impacts of various waste management techniques such as landfill gas, incineration, and anaerobic digestion,
- determining the most suitable waste-to-energy approach that is environmentally sustainable for the city of Bahir Dar, and
- making suggestions and recommendations based on findings for a waste management system that has minimal environmental impact.

1.4 Significance of the study

There are key areas that are predicted to make this study useful. First, the research will advance theoretical knowledge of the general characteristics of municipal solid waste and the issues encountered in the impact of the management of municipal solid waste on the entire population. Second, it will provide policy makers, public administrators, solid waste managers, municipal leaders, researchers, and environmental protection agencies with some information that they can use as a starting point for improvement of current solid waste management, the reduction of associated issues, and awareness of practices in the study area. Researchers that want to undertake in-depth, comprehensive investigations in the city or another study region may use the study as a springboard to establish baseline data for their subsequent work.

1.5 Scope of the study

The scope of this study is limited to identifying the most effective waste-to-energy methods, including landfill gas, incineration, and anaerobic digestion, using the Life Cycle Assessment methodology. It will also consider the environmental consequences of each method and determine the optimal waste-to-energy technique. However, it is worth noting that this study will not take into account any seasonal fluctuations in waste collection and characterization.

2. LITRATURE REVIEW

2.1 Life Cycle Assessment

In the late 1960s and early 1970s, when environmental concerns like pollution management, waste accumulation, resource depletion, and energy efficiency first gained widespread public attention, the concept of LCA first emerged [11]. LCA techniques were mostly used during this time to assess how environmentally friendly product development procedures were in sectors like consumer product design, equipment manufacturing, and automotive design. The necessity to ascertain the energy and material requirements of products gave rise to the idea of life cycle inventory analysis in the 1960s. The Coca-Cola Company ordered the first LCA study in 1969 to determine the amount of waste produced during the production and use of brewery packaging materials. Its use soon expanded to include data on ecological and human toxicity, global warming, acidification, eutrophication, and resource depletion. The affects are then evaluated for their importance and the proper inferences are made. The process of gathering environmental loads, analyzing and interpreting their effects, and drawing conclusions makes up the life cycle assessment (LCA). In order to evaluate the environmental effects of a product, material, or process system throughout the course of its entire life cycle, from the extraction of raw materials through the production and use phases to waste disposal, a tool known as life cycle assessment (LCA) is utilized. It is a comprehensive strategy predicated on the idea that "the actual magnitude of the environmental load can only be known if all phases of a product or service are accounted in at the end."[12]. This method or viewpoint enables LCA to extend beyond the locations of product production and minimizes the potential transfer of environmental costs throughout phases of a product's life cycle, which motivates manufacturers to go above and beyond compliance. LCA is a crucial environmental management EA tool. Almost all industries have used it, including manufacturing, supply chain optimization, agriculture, waste management, and marketing. The four interrelated steps of LCA investigations, as specified by the ISO 14040 series, are I goal and scope definition, (ii) inventory analysis, (iii) effect assessment, and (iv) result interpretation (ISO, 1997). The aims, target audiences, and system boundaries of the particular LCA research must be defined as part of the goal and scope definition process. The process of gathering and synthesizing information on energy flows and physical material flows at various points in the life cycle of a system of goods is known as inventory analysis (ISO, 1997). The impact assessment stage of an LCA aims to analyze the importance of potential environmental repercussions of different flows of energy and materials and categorize them according to those impacts, such as ozone depletion, climate change, acidification, ecotoxicity, and resource depletion [13].

2.1.1 LCA Methodologies and Frameworks

To bring uniformity and permit comparison between the findings of various LCA studies, the International Organization for Standardization (ISO) has defined standard frameworks in the ISO14040. This framework states that the four primary stages of LCA are the establishment of goals and scope, inventory analysis, impact assessment, and interpretation (see figure 1).

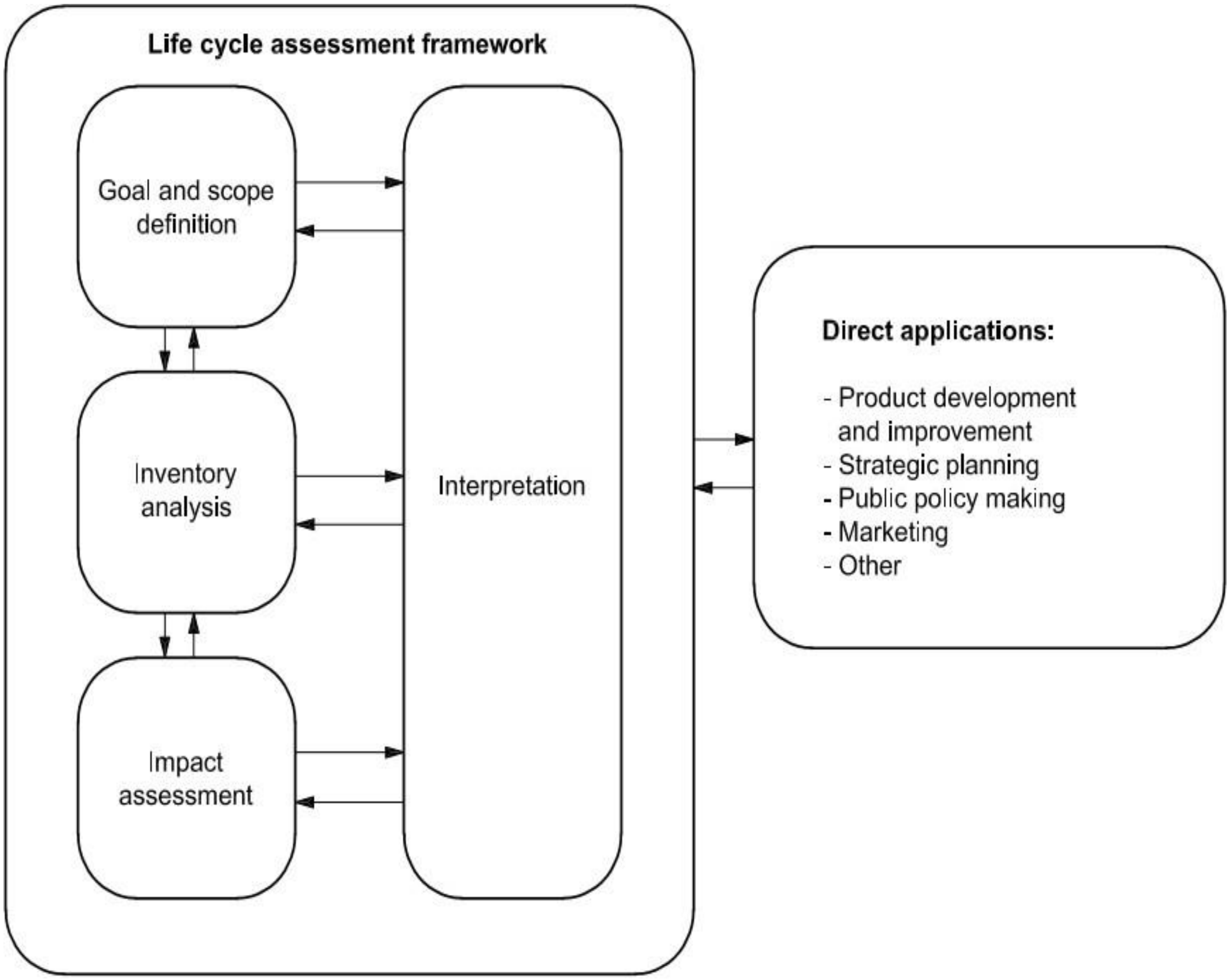


Figure 1: Schematic representation of Life cycle assessment methodology frameworks[14]

2.1.2 Goal and Scope Definition

Any LCA study's initial phase is the determination of its goals and scope. The purpose of an LCA study outlines its objectives, target audience, and potential application domains for its findings. The functional unit, system boundaries, and data quality standards are determined when determining the study's scope. The performance of the outputs of the under-investigation product system is measured by the functional unit (ISO, 1997). The stage of defining the goal and scope is a crucial one in the LCA process since it establishes several crucial methodological elements like the functional unit, modeling techniques, system limits, allocation, and data needs. Which unit processes are included in the LCA are determined by the system boundaries, which must be consistent with the study's objective (ISO, 1997). Choosing which life cycle phases should be included in the LCA research is a key aspect of boundary setting.

2.1.3 Inventory Analysis

Environmental loads (resource consumption and emissions) inside the specified boundaries of the product system are identified and quantified once all pertinent methodological decisions have been made. As a result, during the inventory analysis phase, processes are identified, systems are modelled, and then inventories (or flows) of individual unit processes are compiled and quantified throughout the phases of the life of a product system (ISO, 2006a). LCI studies or LCI datasets can be the results of inventory analysis (EC-JRC, 2010). Results from LCI studies can be transformed into environmental impacts during the impact assessment phase or used for process analysis, material selection, product evaluation, product comparison, and legislation. To put it simply, inventory analysis is the accounting of every component of the target product system. A typical inventory analysis includes the following four steps: Create a flowchart of the processes being analyzed, then create a plan for data collection, gather the data, evaluate the findings, and report them [15].

2.1.4 Impact Assessment

Results of inventory analysis are translated into their possible environmental implications during the impact assessment phase (ISO, 2006). Impact categories, impact category indicators, and characterization models are defined in the LCA study by the use of the LCIA approach. The assessment's environmental concerns are referred to as the impact categories, while category indicators are the impact categories' scores stated in the appropriate substances and characterization models are expressions used to calculate impact factors and indicators [16]. The evaluation of potential effects on the environment and human health due to environmental discharges and resources discovered during the inventory analysis constitutes the impact assessment phase of an LCA research [15]. It seeks to create a connection between the system of products being studied and any potential environmental effects. The problem-oriented (midpoints) approach and the damage-oriented (endpoints) approach, which can also be combined, are two approaches to environmental impact assessment. The primary difference between midpoint and endpoint methods is that they consider various points along the cause-and-effect chain in order to estimate a product system's environmental impact.

2.1.5 Interpretation

The fourth mandatory phase in ISO 14040 and ISO 14044 standards is referred to as "life cycle interpretation" and is defined as the "phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations." The aim of the interpretation phase is to ensure that the intended users of the LCA studies will find the results of the studies credible [17].

2.2 Life Cycle Assessment Tools

Life Cycle Assessment (LCA) is a complex and advanced method used to assess the environmental impact of a product or service throughout its life cycle. To perform an LCA, various software and tools are available which use different impact assessment methods and databases [18]. The choice of LCA tools depends on some criteria such as:

Product and Life Cycle Definition: LCA tools can be chosen based on product definition function because life cycle can be built through the user interface of life cycle builder in a graphical way or in comprehensive and flexible life cycle structured framework [19].

Assessment Result Presentation: Other criteria for choosing LCA tools is assessment presentation method. User may choose LCA tool which give the user comprehensive and detailed LCA results[19].

Databases: Availabilities to use reliable databases and to select the databases suitable for a particular application highly affects the quality and accuracy of the assessment results.

Cost: the selection criteria of software tools depend on the cost of the software as well as the cost of the databases.

Assessment Categories and available LCIA Methods: having large number of assessment methods enable the user to select assessment methods which can enhance their Life cycle Impact assessmen [19].

2.2.1 SimaPro Software

SimaPro is a commercial LCA software tool designed according to the ISO standard to undertake the LCA analysis by Consultants, Netherlands. SimaPro is used to analyze the impact of the life cycle stages to the overall environmental load produced by the systems [20]. SimaPro contains several databases, which includes ecoinvent database, contains numerous processes and impact assessment methods to allow life cycle analysis of complex systems in an organized way [21].

2.2.2 ORWARE

ORWARE (Organic Waste Research) is a computer simulation model developed for use as a tool in research of waste management systems and environmental analysis of waste management. The model can be used for calculation of environmental effects, flows of substances but also economic cost of different waste management systems. ORWARE was developed in collaboration between KTH Industrial Environmental Protection, IVL Swedish Environmental Research Institute, JTI Swedish Institute of Agricultural and Environmental Engineering, SLU Agricultural Engineering and SLU Economics [22].

2.2.3 OpenLCA

OpenLCA is an open-source life cycle assessment tool which is widely used because of it’s free from payment unlike other LCA tools which need payment to access the software. The other thing regarding LCA is it has database called Elcd which is made to assess energy systems including waste to energy systems

2.2 Solid Waste

The EU's 2008/98 EC waste framework directive established concepts and definitions for waste management that focus on trash recovery and recycling. Additionally, the EU directive has created waste guidelines that outline when waste becomes into by distinguishing between waste and the outcomes of products, and not how waste is created. Article 3(1) of the aforementioned directive defines waste as "any material or thing the holder discards, wants to discard, or is obligated to trash." But these ideas must be viewed broadly as separate notions of waste law.

Any solid material in the material flow pattern that is discarded by society is considered solid waste. A solid material is what? It is a substance with a sizable angle of repose. One indicator of a substance's fluidity is the angle of repose. If left to stand unrestrained, a material that does not display an angle of repose will assume a flat horizontal surface. The angle of repose is the angle that the pile's surface makes with respect to horizontal [23]. Garbage, rubbish, sludges, and other solid waste products from commercial and industrial operations as well as from neighborhood activities. It does not include silt, dissolved or suspended particles in industrial wastewater effluents, dissolved materials in irrigation return flows, or other typical water contaminants. It also does not include solids or dissolved material in home sewage. (Pitchel, 2005). Waste is anything produced unintentionally as a result of human activity or, more broadly, of any living creature. Humans constantly transform the resources they have at their disposal into something they can assimilate in order to survive, which results in the creation of garbage. Natural processes don't produce built-up garbage. Chemical components create and destroy a wide range of structures as part of the material's closed natural cycle, leaving no waste that cannot be absorbed by nature. It is human interference that disrupts this naturally occurring material cycle since in order for man to acquire things, he must advance and raise his standard of living. After extracting the raw materials, man processes and uses them, leaving behind a variety of byproducts that cannot be digested but rather build up or are deposited in locations frequently without any kind of treatment [24].

2.2.1 Municipal Solid Waste

MSW, often referred to as domestic waste or occasionally household garbage, is produced by a variety of sources within a community and is not just produced by a single customer or a single household. Residential, commercial, institutional, industrial, and municipal sources produce MSW (Pitchel, 2005). The term "municipal solid waste" (MSW) refers to a diverse range of trash generated in metropolitan settings. This trash differs from region to region in terms of its composition and nature. The level of living standards and way of life of the locals, as well as the presence of a particular kind of natural resource, all affect how much and what kind of solid waste is produced. Municipal garbage can be divided into two main groups: organic waste and inorganic waste.

2.3 Solid waste management

The management of solid waste is closely related to environmental and socioeconomic factors. The finest solid waste management solutions are correlated with sustainable development in the solid waste sector. Solid waste stream is exploited as an energy recovery resource nowadays because of inventive technology advancement and changes in perspective, which also secures the recovery of natural resources. Being heavily reliant on the extraction of natural resources while ignoring the formation and management of trash might have negative consequences. Global climate change has forced us to use natural resources sustainably and to create garbage or technologies that actually ensure sustainability.

2.3.1 Waste management hierarchy

Policymakers have utilized the waste management hierarchy, a framework that takes into account items from their "cradle" to their "grave," to rank waste management strategies according to their environmental advantages. Typically, the waste hierarchy is created to identify the important components of an ISWM plan. The hierarchy is based on environmental principles that state that waste should be handled differently depending on its characteristics, i.e., a certain amount should be avoided by reducing the waste's content or by reusing the waste; another portion of the waste stream should be converted into secondary raw materials; some parts can be composted or used as a source of energy; and the remaining may be landfilled. This sequence depending on the environment does not reflect reality. In fact, a significant amount of rubbish is burned outdoors or, worse, disposed in an uncontrolled manner in poor nations.

These solutions are obviously not part of the waste hierarchy due to their unacceptable high levels of environmental harm. The European Union Solid Waste Strategy specifies the following hierarchy of alternatives, which is taken into account while choosing the waste management strategy.

1.Waste minimization with a prevention-minded mindset and waste reduction at the source.

2.Reusing and recycling waste.

3.The recovery of energy or raw materials.

4.Wastes are treated.

5.Disposal of treatment waste leftovers and other unavoidable garbage.

Figure 1: Schematic representation of waste management hierarchy [25]

2.4 Waste to Energy Waste Management Systems

In the hierarchy of waste management, waste to energy is in charge of turning non-recyclable waste into useful things like heat, power, and/or transportation fuels. WTE technology can handle a variety of waste types, including semi-solid, liquid, and gaseous waste. Prior to a few years ago, waste was viewed as useless; however, with the aid of WTE technologies, it was transformed into a heat source and is now regarded as a feedstock for such procedures [26]. Utilizing trash as feedstock for a WTE facility not only reduces the amount of space needed for landfills and the associated expenses of waste management, but also makes the waste useful by allowing it to be turned into useful fuels, fertilizers, and energy.

2.4.1 Landfill gas

The most typical method of handling MSW throughout the world is to dispose of the material in landfills (Williams, 2005.). A landfill is a specially designed location where garbage is dumped.

The landfill may be constructed on top of the earth or may be a hole in the ground. A sanitary or engineered landfill is used to dispose of trash while keeping the waste's effluent isolated from the surrounding environment. The breakdown of organic material that occurs in landfills and biogas reactors follows the same general pattern. The difference is that because the circumstances in the biogas reactor are optimal, biogas production from anaerobic digestion occurs more quickly and in a regulated reactor. The gas generated from landfills could be used as a substitute energy source and to cut greenhouse gas emissions [28]. Methane is a greenhouse gas that is 21 times more potent than carbon dioxide [29]. The collection and use of landfill gas is primarily linked to the emission of biogas and percolated leachate, two pollutants. If a landfill is close to its consumers, it would be viable to use the gas it produces to make money. The facility's turbines or generators account for 60% of the plant's costs, thus either the users must be close by or pay more for power (FCM, 2004). LFG plays a significant role in sustainable environmental, socio-economic, health, and safety benefits. The utilization of LFG might reduce smog, odor, and GHG emissions, which can enhance indoor and outdoor air quality. The generation of electricity from LFG and feeding into the distribution grid can reduce the constraints on coal-fired power stations, thus reducing CO_2 emission and other pollutants that contribute to poor air quality and climate change [30].

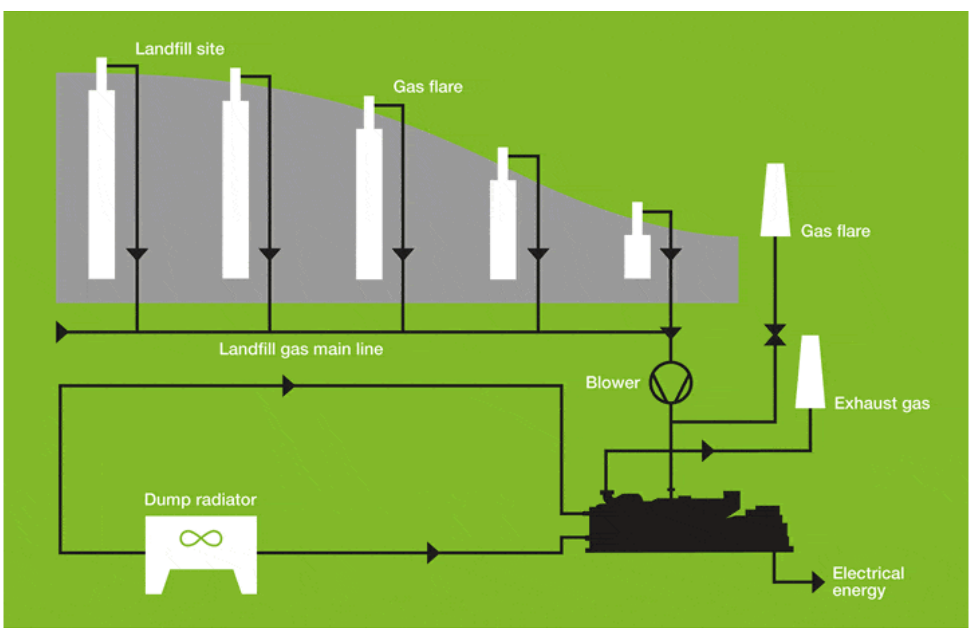


Figure 2: Schematic representation of landfill gas system [31]

2.4.2 Incineration

Incineration is one the most integral part of MSW management in many countries worldwide. around 65–80% of the energy stored in organic materials can be recovered in the form of heat that can be used in other power producing facilities based on thermal supplies. [32]. Municipal solid waste (MSW) is incinerated in large-scale facilities where the gases and other byproducts, such bottom ash, are managed to reduce the environmental impact [33]. The MSW's combustible portion is oxidized in an incinerator facility so that energy can be recovered. Municipal solid waste incineration in planned incinerator plants with treatment of flue gases and waste water is a technique that is increasingly popular [34]. The heating value is a significant factor affecting the energy potential in MSW. The chemical makeup of the various fractions determines the heating value, which is a measurement of the energy that the waste contains. The incinerator's combustion efficiency is controlled by the heating value. The use of incinerating technology has the potential to reduce waste volume, divert a sizable amount of solid MSW from landfills, recover energy, and utilize a range of chemicals and minerals found in trash. It has the power to eliminate a variety of harmful chemicals included in solid waste [35]. Whereas, Heavy metals and the possibility of dioxins in gases, ash, and water are potential risks associated with trash incineration. Communities that are adjacent to facilities that burn solid waste experience health issues and are a source of environmental degradation [36].

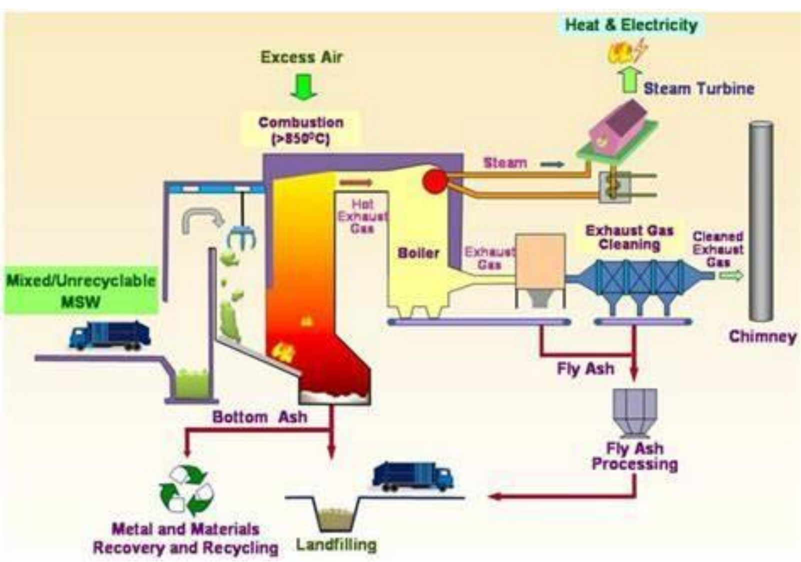


Figure 3: Schematic representation of MSW incineration plant

2.4.3 Anaerobic Digestion

By digesting biomass in an anaerobic environment, bacteria carry out anaerobic digestion. Different bacterial species cohabit and break down the complex organic waste in various phases [37]. One of the products utilized in this process is methane gas which is relevant, is one of the products produced by this process. The entire anaerobic digestion process produces biogas; which comprises methane and carbon-dioxide and a digestate; which is also rich in some macro-nutrients (nitrogen and phosphorus) needed for plant growth [38]. In the course of anaerobic digestion, proteins, fats, carbohydrates, and lipids in organic matter go through a number of metabolic changes. In order to create new cell protoplasm, anaerobic organisms utilize the carbon, nitrogen, potassium, and other nutrients found in organic material [39]. Degradable organic waste streams can be processed via anaerobic digestion. Yard trash, paper waste, food waste, and other organic materials can all be found in the organic percentage. Specifically controlled conditions, such as pH, moisture content, and temperature, are given inside special reactors utilized for the digesting process. Certain controlled settings offer microorganisms a favorable environment, allowing them to multiply and improve the grading process to make methane [40]. Composting biogas digestion is a method for improving soil. Digestate can be used as low-calorie RDF after being dewatered. A pathogen-free final product that can operate as a soil conditioner is stabilized by providing the proper internal system conditions, such as warmth and moisture. The anaerobic digester performs effectively with properly handled wastes, such as the separation of plastics that could pose operational challenges. When handling the material, a bad stench is produced. The market value of the finished product may also be lower since it may contain harmful impurities that are challenging to remove during processing. The digestive system's high processing, handling and storage costs [41].

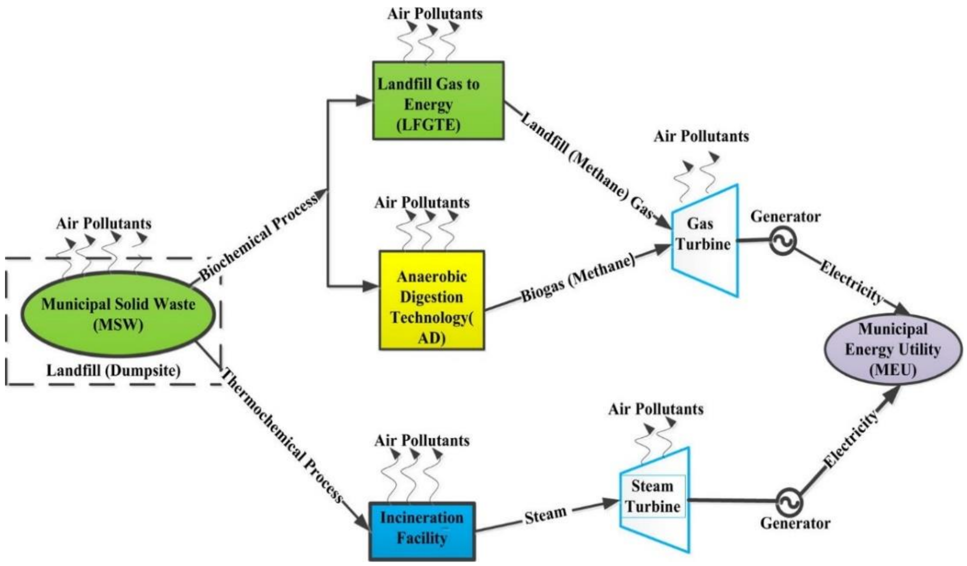


Figure 4: Schematic representation of selected WTE systems [8]

2.5 Application of LCA in Waste to Energy systems

LCA is applicable in WTE systems to compare different waste to energy systems and select the best and environmentally sustainable system. To compare also resource consumption, energy consumption, emission. LCA is used to study and assess resource depletion greenhouse gas emissions. The other application of LCA in waste to energy system is to identify potential hotspots in environment and resource consumption to find room for improvement in that area. Findings of LCA can be used to assure continuous improvement and also, they can be used in policy making, public awareness and engagement of stakeholders.

3. Materials and Methods

3.1 Study Area

The Amhara National Regional State (ANRS) in northern Ethiopia has Bahir Dar as its capital. It is close to Lake Tana, the Blue Nile's source, and is a popular tourist attraction. The Bahir Dar City Administration's metropolitan region is located around 25 kilometers from the city's center. It has three outlying communities. They are: Tis Abay in the South East, Meshenti in the South West, and Zegie in the North. Geographically, it is situated between 37°15' and 37°40' E East longitudes and 11°35'36"N North latitude. Bahir Dar is one of the highly expanding and rapidly growing cities of Ethiopia. It is also known that Bahir Dar is naturally beautiful because of its establishment around Lake Tana and Abbay River, which are the homes of many fauna and flora. Moreover, Lake Tana holds of many monasteries, which are one of the most tourist destination sites in the country. Bahir Dar City growth is increasing rapidly after it becomes the capital city of the Amhara National Regional State. Currently, Bahir Dar is chosen as a good place to dwell and work in the country. Due to good weather condition, suitable for the health and good people with good culture that respects others. Many people from the rural and other cities are flowing to it.

3.2 Materials

The MSW garbage parts will be weighed using a spring mass balance in an open dump site area. the composite MSW sample will be weighed using a digital beam balance. For sample collection and laboratory testing, a bag and glove will be utilized. Oven drier, will be used to measure the sample's moisture content. Muffle furnace, will be utilized to assess the volatile matter and ash composition of a mixed MSW sample. When anything goes into the furnace, a crucible is used to hold it. Plastic bags will be used to group waste materials into relevant groups.

3.3 Methods

3.3.1 Waste sample collection

The sample waste is collected from each sub-cities and selected kebeles from each sub-city. The sample collection was conducted from composite waste that is collected by workers recruited by city administration workers before it is loaded in to trucks that takes it to the dump site. The waste collection takes place in all of six sub cities of Dar City by randomly sampling kebeles from each sub-city**. (See appendix 2)**

There are quasi-transfer stations in each kebeles in which the wastes are put before loaded in to trucks. The waste samples are taken in quasi-transfer stations-based on ASTM method.

3.3.2 Sample Waste Characterization

The first step was to gather a random sample of waste from a collection site in the city of Bahir Dar, which will be used as the source of the data. Waste characterization is a technique for identifying the kinds of substances and their proportional amounts in a waste stream. Characterization provides additional insight into information such as the amount of moisture, ash, fixed carbon, and volatile matter in waste. Using established methods, the contents of moisture, ash, volatile matter, and fixed carbon will be measured.

Moisture content

Moisture content is an important factor that can affect the energy content of Municipal Solid Waste (MSW). Higher moisture content typically leads to lower energy content because energy is required to evaporate the excess water during combustion. Municipal solid waste (MSW) sample moisture content is measured using the oven dryer method. MSW representative samples were gathered and divided based on composition. The samples were then heated to a particular temperature of 110°C and dried there for one hour. the samples were weighed before and after drying, and the difference in weight was used to compute the moisture content. Several samples were also tested, and the moisture content was estimated. The moisture content of MSW, which is a crucial component impacting the energy content during combustion, may be learned a lot from the contents of the oven drying water samples.

The weight loss that will occur when a sample is dried in a laboratory oven at 110 °C for 1 hour will be used to calculate the moisture content.

Volatile matter

By measuring the weight loss following the combustion of around 5g of MSW at 950°C for 6 minutes, the volatile matter will be identified.

Ash content

The samples will be then roasted at 750 °C for at least three hours in a laboratory ash furnace to ascertain the ash concentration.

Energy content

A methodology called proximate analysis will be used to evaluate the energy content of municipal waste. On the basis of the weight percentage of volatile matter and fixed carbon, proximate analysis models will be produced (Alem, 2007).

$LHV=45B - 6W$

Where B=combustible volatile matter W=water (% dry basis)

Bento's model equation

$LHV = 44.75B-5.85W + 21.2$

Where B is the volatile matter

Where W is the moisture content

Where H is the heating value.

The other method is based of physical composition

$LHV= 88.2P+40.5(Fw+T+Y+Pc)-6W$

Where P: plastic

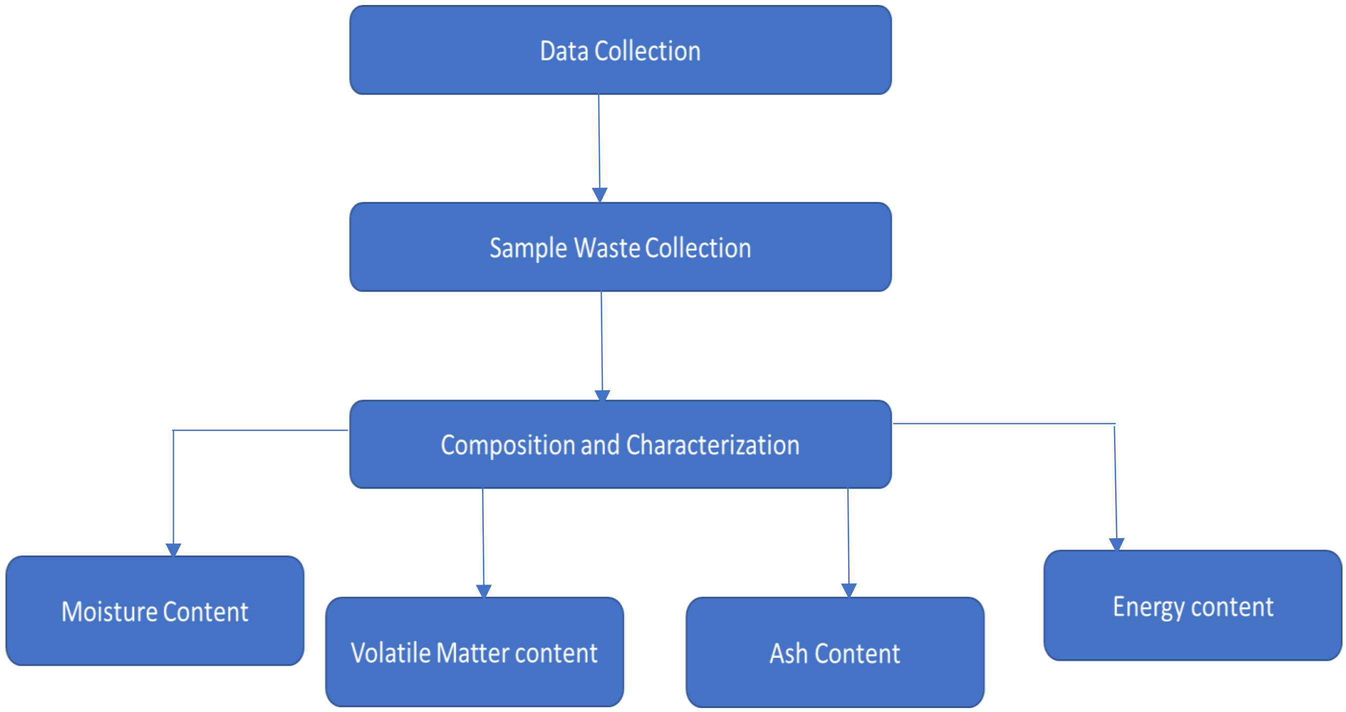
Fw: food waste

T: textile

Y: yard waste

Pc: paper and cardboard

W: moisture content [42]



3.4 Life cycle Impact assessment method

Landfill Gas Model

Collection, sorting, transportation, and landfilling are all included in this. Plan, Process, and Flow will be used to represent LCA. The flow represents the materials and energy in the system, while the process depicts actual actions that take place over the life cycle of the product being studied (such as transportation). The plan represents the system boundaries of the LCA.

Incineration Model

The incineration model took into account collection, sorting, transportation, and incineration. A waste management strategy based on incineration will be created

Anaerobic Digestion Model

The anaerobic digestion model will be taken into account as collecting, sorting and anaerobic digestion.

3.5 Goal and Scope of the Study Method

3.5.1 Goal of Study

The goal of this LCA study will be to assess and compare the environmental impacts of waste to energy in Bahir Dar city by using three different wastes to energy system scenarios. This study's objectives are to evaluate the potential environmental effects of waste-to-energy waste management systems' air emissions and to make management recommendations based on those emissions. The landfill gas, incineration, and anaerobic digestion waste to energy systems will be assessed.

The main purpose of the life cycle assessment is to conduct a comparative analysis of the environmental impacts of landfill gas recovery systems, anaerobic digestion, and waste-to-energy incineration. The assessment will particularly focus on calculating and comparing the potential environmental impacts associated with each waste management system. The goal is to **identify hotspots and possible trade-offs with the environment during the life cycle of each system.** This information will be useful for policymakers, practitioners, and stakeholders to make knowledgeable decisions that will result in more sustainable waste management techniques. Additionally, the assessment aims to address current research gaps and uncertainties in order to improve the field's understanding of sustainability and waste management.

3.5.2 Scope of the study

The focus of this study will be on analyzing emissions from landfill gas, incineration, and anaerobic digestion. The scope of this research is limited by functional unit, system boundary and basic assumptions.

Functional unit: The first task is defining a functional unit needed to build the life cycle assessment model and framework. The functional unit quantifies a standard amount to be compared with all the alternatives that shares this function. Launching a functional unit is initial step in any LCA. The comparison between multiple products and processes is based on functional equivalency. The functional unit for this LCA method in this research is production of **one ton** of municipal solid waste.

System Boundary: The system boundary of the study includes from the collection of municipal solid waste to conversion of municipal solid waste to energy **(see figure 5).**

Assumptions: Environmental burdens resulted from the production of a product before becoming waste is neglected.

Emissions from the construction phase of the facilities are not considered.

Emissions from the transportation of wastes are not considered as the facilities are at equal distance from the collection site.

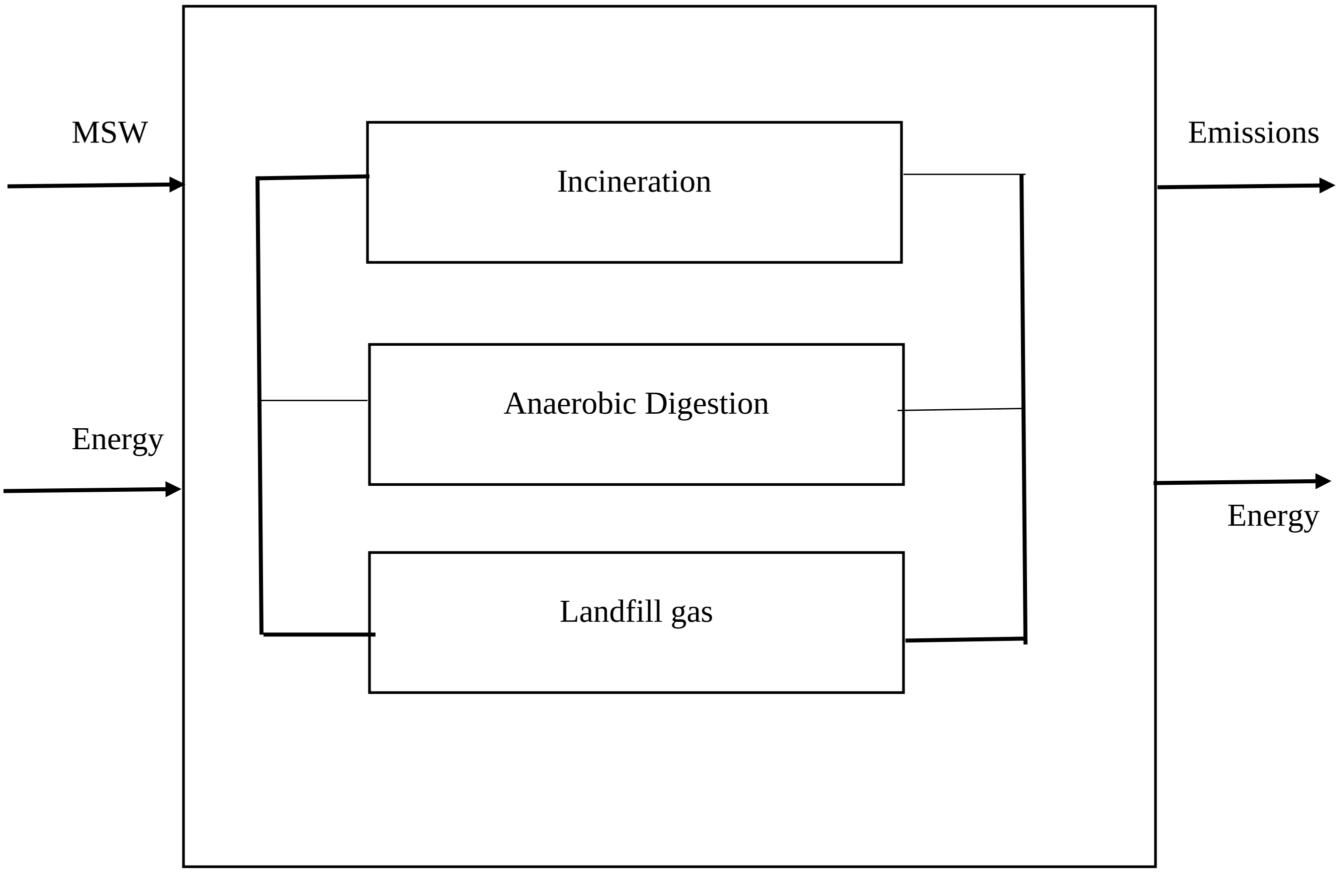


Figure 5: System Boundary

3.6 Life Cycle Inventory Analysis

Inventory analysis in a step involved in life cycle assessment which consists of Life cycle inventories (LCIs) of waste-to-energy (WTE) plants typically includes a broadly assessment of inputs, outputs, and environmental impacts correlated with each stage of the plant's life cycle. LCIs provide valuable data for evaluating the environmental performance of WTE incineration plants and comparing them with alternative waste management options.

Input	Category	Amount	Unit
Calcium hydroxide	Elementary flows/Emission to air/high population density	6.54	kg
Diesel	Energy carriers and	0.42	kg

	technologies/Crude oil-based fuels		
Electricity	Energy carriers and technologies/Electricity	60.2	kWh
Water	Elementary flows/Resource/in water	356	kg
waste incineration of municipal solid waste (MSW)	End-of-life treatment/Energy recycling	1000	kg
Output			
Carbon dioxide, biogenic	Elementary flows/Emission to air/high population density	152.2	kg
Carbon dioxide, fossil	Elementary flows/Emission to air/high population density	62.17	kg
Carbon monoxide	Elementary flows/Emission to air/high population density	0.35	kg
Dioxins (unspec.)	Elementary flows/Emission to air/unspecified	5.06E-07	kg
Dust, unspecified	Elementary flows/Emission to air/unspecified	0.049	kg
electricity from waste incineration	Energy carriers and technologies/Electricity	0.6174	MJ
Fly ash	Elementary flows/Waste/unspecified	150	kg
Hydrogen chloride	Elementary flows/Emission to air/high population density	0.024	kg
msw incineration		1000	kg
Nitrogen oxides	Elementary flows/Emission to air/high population density	1.13	kg
Sulfur oxides	Elementary flows/Emission to air/high population density	0.016	kg

Table 1: Life Cycle Inventory data for incineration

The above table is data obtained from OpenLCA, Elcd database adjusted based on the data of Bahir Dar city municipal waste.

3.7 Impact Categories

3.7.1 Acidification Potential

When MSW is inputted into the environment or is discharged into the atmosphere, anthropogenically derived sulfur and nitrogen, such as NOx or ammonia, are produced.

The effects of AP on biological organisms, ecosystems, and chemicals include acid deposition of acidifying pollutants on soil, groundwater, surface waters, and substances. The main pollutants that cause acidification are SO2, NOx, and NH_3. The natural environment, the built environment, human health, and natural resources are all considered protection zones. Materials that are acidifying have a wide range of effects on the soil, groundwater, surface water, creatures, ecosystems, and materials. To express the AP, SO2 equivalents/kg emission is used.

3.7.2 Global Warming Potential

GWP is defined as the effect of emissions on the radiative forcing (i.e., the atmosphere's capacity to absorb heat radiation). Climate change, which is ultimately brought on by global warming, can have an impact on ecology and human health. The majority of these releases enhance radiative forcing, which raises surface temperatures and is known as the greenhouse effect. Climate change is connected to GHGs in the air. Climate change may have detrimental implications on ecosystem health, human health, and material welfare. The characterization model, which will be chosen for the development of characterization factors, was created by the Intergovernmental Panel on Climate Change.

3.7.3 Eutrophication potential

Phosphate-equivalent is a metric used to gauge a substance's eutrophication potential. The conversion of the chemicals produces the same quantity of phosphate and has the same eutrophication effect. The impact of eutrophication is mostly brought on by NH3 emission.

In both aquatic and terrestrial ecosystems, nutrient enhancement can result in an unintended change in species composition and an increase in biomass production. The term eutrophication refers to all potential effects of exceptionally high levels of macronutrients in the environment, namely nitrogen and phosphorus. All emissions that have comparable effects are included together under the impact category of eutrophication.

3.7.4 Ozone depletion potential

The potential of a material to reduce the ozone layer in the Earth's stratosphere is measured by its Ozone Depletion Potential, or ODP. The main contributors to ozone depletion are man-made chemicals called ozone-depleting substances (ODS), which include methyl chloroform, carbon tetrachloride, halons, and chlorofluorocarbons (CFCs). When discharged into the stratosphere, the chlorine and/or bromine atoms in these compounds catalytically destroy ozone molecules.

A measure of how much damage is a substance can cause to the ozone layer compared with a similar mass of trichlorofluoromethane (CFC-11).

3.7.5 Fossil fuel depletion

The progressive depletion of limited energy sources like coal, oil, and natural gas—which have accumulated over millions of years through geological processes—is referred to as fossil fuel depletion. These fuels are important sources of energy for many human activities, including as industry, transportation, heating, and the production of electricity.

The depletion of fossil fuel reserves due to extraction and combustion raises questions regarding the sustainability of the environment and future energy security. Furthermore, the mining and burning of fossil fuels releases greenhouse gases (GHGs) that contribute to climate change and other environmental effects. Examples of these gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

3.7.6 Ecotoxicity

The term "ecotoxicity" describes a substance's detrimental effects on ecosystems and the microorganisms, plants, and animals that live there. Exposure to pollutants discharged into the environment by human activities including mining, waste disposal, agriculture, and industrial processes can have these impacts.

Plastics, industrial chemicals, heavy metals, and medications are examples of common ecotoxicants. Through bioaccumulation and biomagnification along the food chain, these compounds can accumulate in soil, water, and the air, upsetting ecological processes and posing dangers to biodiversity and human health.

4. RESULT AND DISCUSSION

4.1 waste composition

Waste category	Dagmawi Menelik	Fasilo	Gish Abay	Belay Zeleke	Tana	Atse Tewodros
Food waste	58.05	45.46	53.59	63.13	58.52	56.31
Plastic	7.42	8.53	7.44	5.85	5.45	6.63
Paper and Cardboard	11.96	10.94	9.88	8.01	9.05	8.44
Textile	3.30	3.31	2.9	3.95	3.33	3.16
Glass	1.07	3.68	1.2	4.01	1.48	0.76
Metals	1.04	0.83	1.27	1.01	0.63	1.04
Yard	22.97	27.22	23.50	14.02	20.61	23.62

Table 2: Average MSW composition

The solid waste generated in the Dagmawi Menelik sub city is mostly dominated by food waste about 58.05% followed by 22.97%-yard waste thirdly paper and cardboard 11.96%, plastic waste accounts for 7.42%, textile wastes accounts about 3.30% of the waste the glass and metal wastes are relatively much lower as compared to other waste compositions which are 1.07 and 1.04 percent respectively. The municipal solid waste generated in Fasilo sub city is mostly food waste which accounts about 45.46% followed by yard waste which is 27.22% paper and cardboard is 10.94% of the waste, plastic waste accounts about 8.53% of the waste, textile waste is about 3.3% of the waste the glass waste is 3.6% and metal waste is 0.83%. The solid waste generated in the Gish Abay sub city is mostly food waste about 53.59% followed by 23.5%-yard waste thirdly paper and cardboard 9.88%, plastic waste accounts for 7.44%, textile wastes accounts about 2.9% of the waste the glass and metal wastes are relatively much lower as compared to other waste compositions which are 1.2 and 1.27 percent respectively. The municipal solid waste generated in Belay Zeleke sub city is mostly food waste which accounts about 63.13% followed by yard waste which is 14.02% paper and cardboard is 8.01% of the waste, plastic waste accounts about 5.85% of the waste, textile waste is about 3.95% of the waste, the glass waste is 4.01% and metal waste is 1.01%. The solid waste generated in the Tana sub city is mostly dominated by food waste about 58.52% followed by 20.61%-yard waste thirdly paper and cardboard 9.05%, plastic waste accounts for 5.45%, textile wastes accounts about 3.33% of the waste the glass and metal wastes are relatively much lower as compared to other waste compositions which are 1.48 and 0.63 percent respectively. The municipal solid waste generated in Atse Tewodros sub city is mostly food waste which accounts about 56.31% followed by yard waste which is 23.62% paper and cardboard is 8.44% of the waste, plastic waste accounts about 6.63% of the waste, textile waste is about 3.16% of the waste the glass waste is 0.76% and metal waste is 1.04%.

Based on the compositional analysis the highest percentage of food waste is recorded in Belay Zeleke sub city and the lowest is recorded in Fasilo sub city. The highest percentage of paper and cardboard waste is recorded in Dagmawi Menelik sub city and lowest recorded in Belay Zeleke sub city. The highest percentage of plastic waste is recorded in Fasilo sub city and lowest recorded in Tana sub city. The highest percentage of textile waste is recorded in Belay Zeleke sub city and the lowest is recorded in Gish Abay sub city. The highest percentage of glass waste is recorded in Belay Zeleke sub city and the lowest is recorded in Atse Tewodros sub city. The highest percentage of metal scrap waste is recorded in Gish Abay sub city and the lowest is recorded in Tana sub city. The highest percentage of yard waste is recorded in Fasilo sub city and the lowest yard waste is recorded in Belay Zeleke sub city.

4.1.1 Statistical analysis

The statistical analysis is involving both parametric and non-parametric tests to determine whether there is significant difference or not in municipal waste composition of the six sub cities of Bahir Dar town. The non-parametric test carried out is Kruskal Wallis test and parametric test carried out is one-way ANOVA. The test is done using python programming language using the statistical library tool SciPy (appendix).

P-Value	T- statistic	Mean Rank	Sum of rank
0.99805	0.277194	21.428571	150
		23	161
		21.57142	151
		22.285714	156
		20.71428	145

		19.85714	139

Table 3: Kruskal Wallis test result of MSW data

For the test statistic, the P-value is 0.99805. The P-value is the likelihood of witnessing the test statistic, or an additional extreme, in the event that the null hypothesis is true. Put another way, it indicates the probability that the data would be observed in the event that there were no group differences. The extremely high P-value of 0.99805 indicates that there may not be a significant difference between the groups under comparison.

One way ANOVA

Statistic	Value
F – statistic	0.0023
P-Value	0.999

Table 4: One way ANOVA test result of MSW data

From the one-way ANOVA result we can infer that there is no significant difference in waste composition between sub cities.

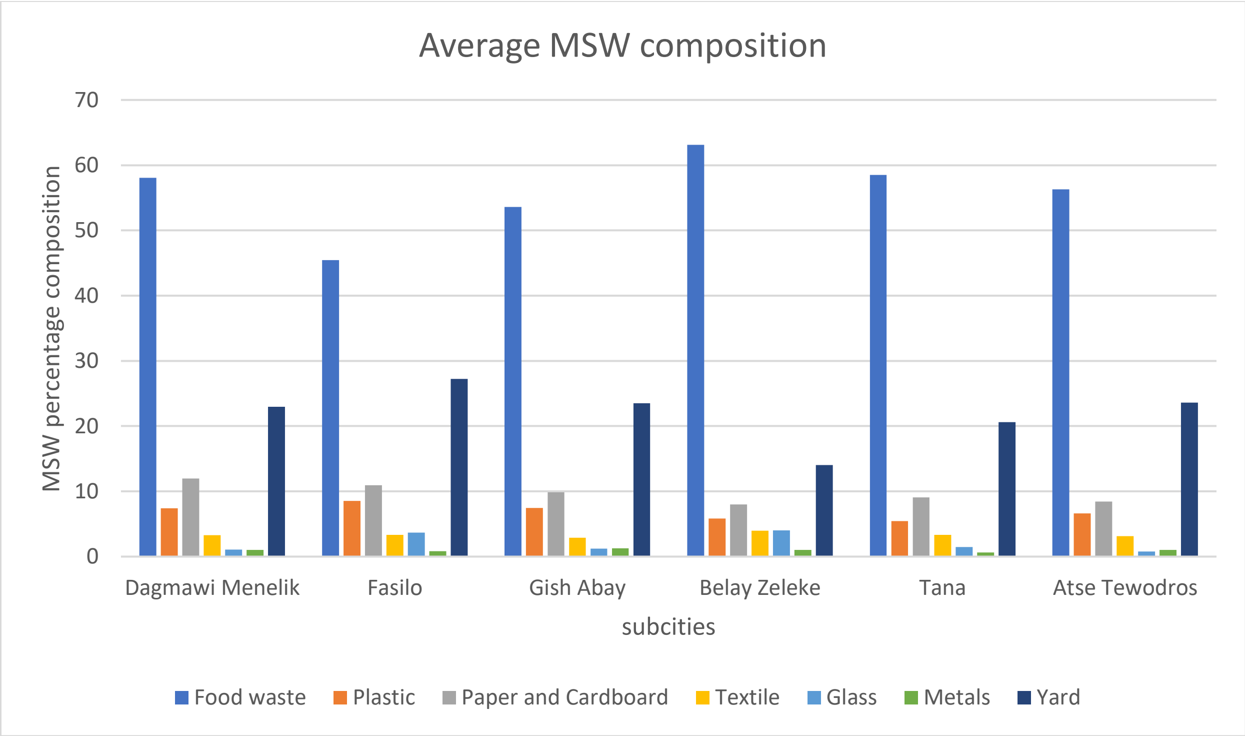


Figure 6: Average MSW composition of each sub city

4.2 Proximate Analysis Result

The proximate analysis result comprised of moisture content, volatile matter content, ash content and fixed carbon of the sample waste. The ASTM method was used to conduct the proximate analysis of the sample waste. The proximate analysis results are presented in the table below.

Waste	Moisture content (%)	Volatile matter (%)	Ash content (%)	Fixed carbon (%)
Food waste	61.20	10.52	11.10	17.18
Plastic	10.31	68.4	4.61	16.68
Paper	14.62	45.02	5.25	35.11
Textile	19.42	39.63	7.43	33.52
Yard waste	39.84	24.56	8.30	27.3

Table 5: Proximate Analysis result of MSW

From the above table food wastes have higher moisture content (61.4%) followed by yard waste which is 39.84%. the higher moisture content indicates that much additional energy will be needed to combust the solid waste which means additional fuel will be required to convert it to energy. From the table we can see that plastic waste have highest volatile matter content followed by paper and cardboard. Ash content refers to the waste that is left out with out combusted during the burning of sample waste in the muffle furnace. The higher the ash content means the lower the flue gas and vice versa. Fixed carbon content refers to the carbon remaining of the surface. From the result textile waste has higher fixed carbon.

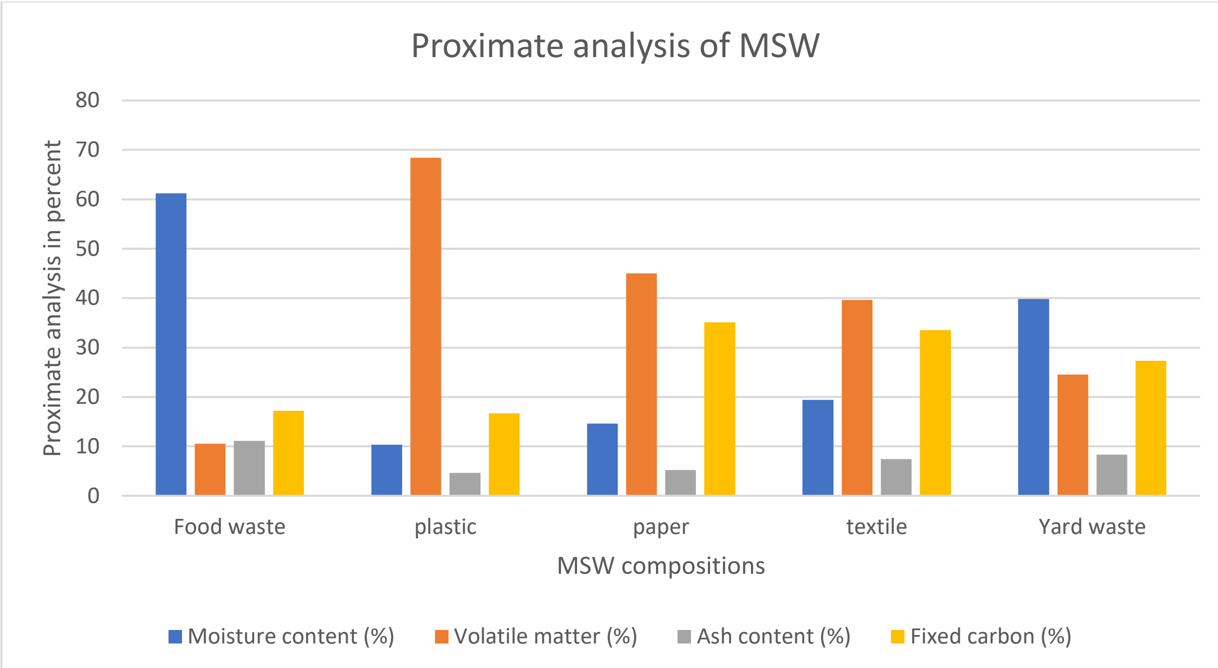


Figure 7: Proximate analysis of the MSW

4.3 Energy Content Determination

The energy content is determined based on proximate analysis model using the equation

LHV=44.75Vm-5.85Mc+21.2

Where Vm: Volatile matter content

Mc: Moisture content

Waste	Moisture content (%)	Volatile matter (%)	LHV
Food waste	61.2	10.52	133.95
Plastic	10.31	68.4	3021.78
Paper	14.62	45.02	1950.31
Textile	19.42	39.63	1681.03
Yard waste	39.84	24.56	887.19

Table 6: Energy content of the MSW by using proximate analysis result

The next step is to formulate multiple regression model to predict the energy content. The dependent variable is energy content and the independent variables or the predictor variables are moisture content and volatile matter content.

Energy content = $\beta 0$ + $\beta 1$*Moisture content+ $\beta 2$* Volatile matter content

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	21.185656	0.0074379	2848.3416	1.2326E-07	21.153653	21.21766	21.15365	21.21766
Moisture content (%)	-5.8497944	0.0001148	-50950.85	3.8521E-10	-5.850288	-5.8493	-5.85029	-5.8493
Volatile matter (%)	44.750084	0.0001115	401379.49	6.2071E-12	44.749604	44.75056	44.7496	44.75056

From multiple point regression result using excel data analysis tool kit

$\beta 0$ is the intercept which is 21.185656

$\beta 1$ and $\beta 2$ are the coefficients which are -5.8497944 and 44.750084 respectively. the coefficients indicate that for moisture content the energy content decreases by 5.849 units when one unit of moisture content increases and the energy content increases by 44.75 units when the volatile matter content increases by one unit.

Now we substitute the coefficients into the regression equation and compute the energy content.

Energy content = 21.185656 - 5.849744*moisture content + 44.750084*volatile matter content

Waste	Moisture content (%)	Volatile matter (%)	LHV
Food waste	61.2	10.52	133.952
Plastic	10.31	68.4	3021.774
Paper	14.62	45.02	1950.311
Textile	19.42	39.63	1681.029
Yard waste	39.84	24.56	887.806

Table 7: Energy content of MSW based on regression model

Creating excel dataset to compare the manually computed and the predicted value of energy content.

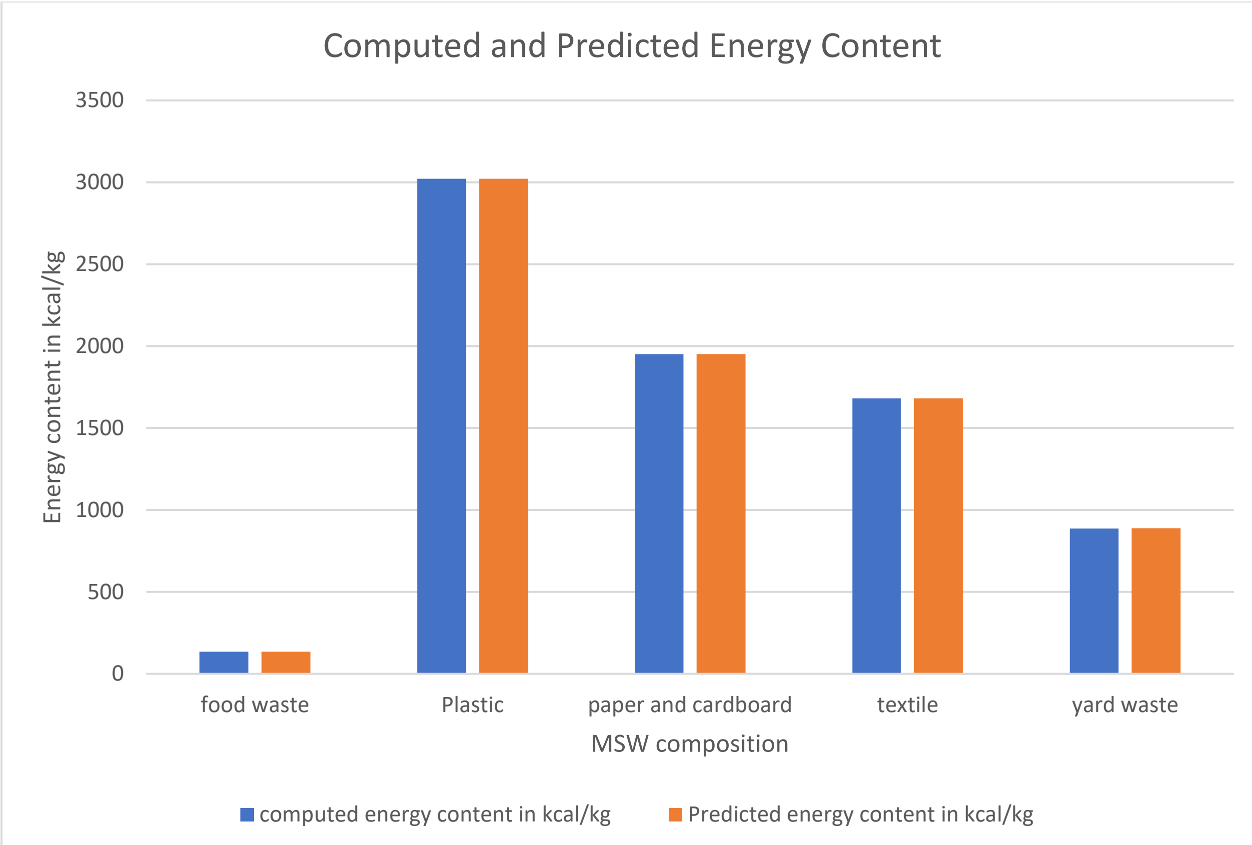


Figure 8: computed and predicted energy content of the MSW

The figure indicates that the computed and the predicted energy content are almost the same, which indicates that the adjustments are not needed to match the predicted and computed energy content value.

4.5 Waste generation

The waste generation data is collected by united nation environmental program in 2010. Based on the consecutive year data forecast model was done by using excel.

Year	waste generation(tons)	population
2010	98.5	218975
2011	105	233427
2012	112	248833
2013	119.4	265256
2014	129.5	287763
2015	135.6	301425
2016	144.6	321319
2017	154	342526

2018	164.4	365333
2019	175.2	389232
2020	186.7	414921
2021	199	442306
2022	212.2	471498
2023	214.5692	476833.9

Table 8: Waste Generation of Bahir Dar City

It’s is clearly visible the population and the waste generation are directly proportional and also the population and the waste generation is increasing in rapid manner

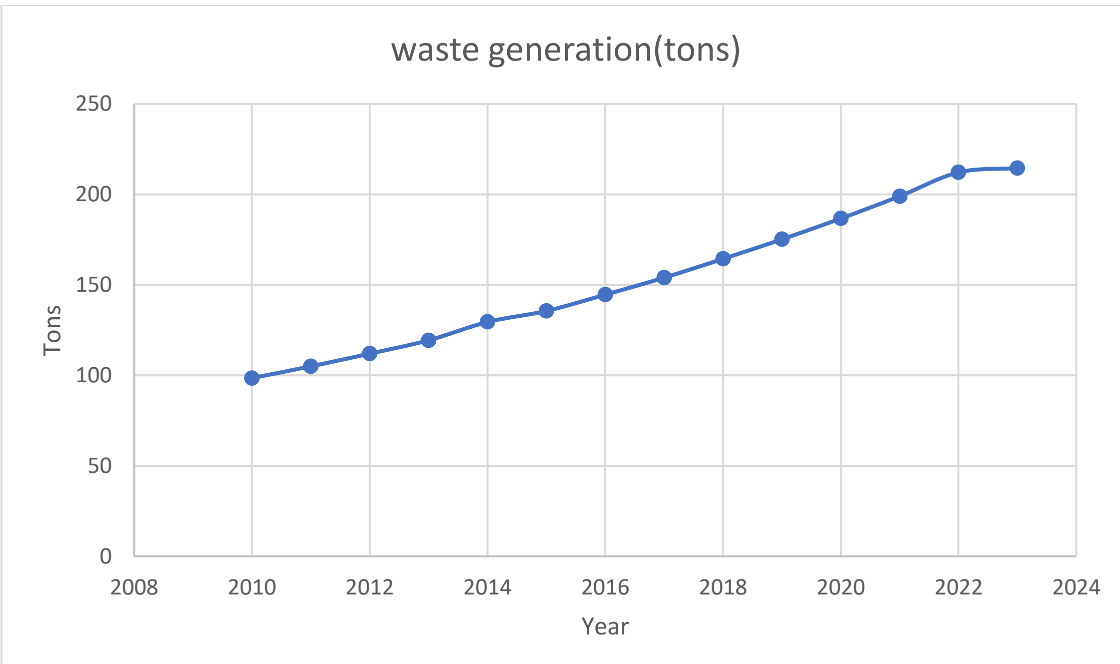


Figure 9: Waste Generation of Bahir Dar city

4.6 Result of Life Cycle Assessment

4.6.1 Environmental Impacts of Incineration

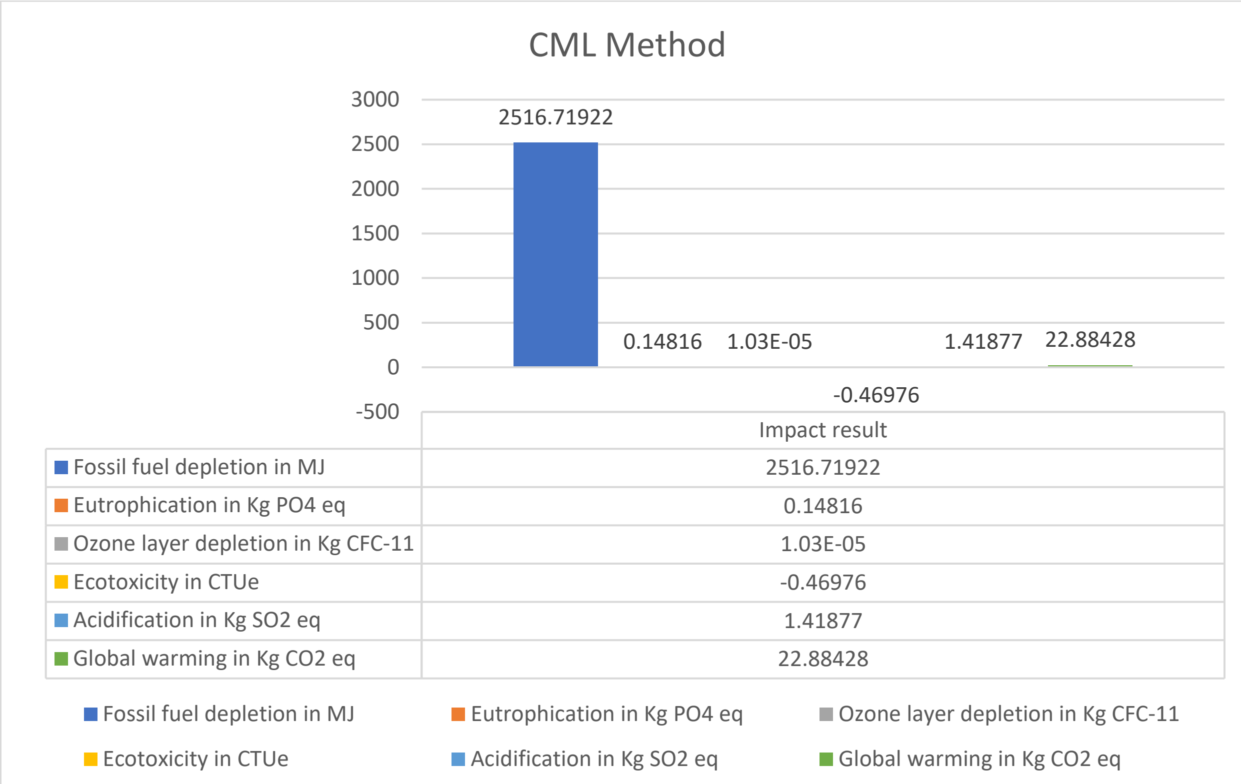


Figure 10: potential environmental impacts of incineration by CML method

Both positive and negative environmental effects are shown by the CML method study of the impact outcomes for incineration. Incineration has certain advantages, such a low potential for eutrophication and little loss of ozone, but it also has some serious disadvantages, like a heavy dependency on fossil fuels, an acidic effect, and large greenhouse gas emissions that contribute to global warming. Consequently, in order to fully comprehend the environmental sustainability of incineration as a waste management option, a thorough assessment taking into account each of these elements is necessary.

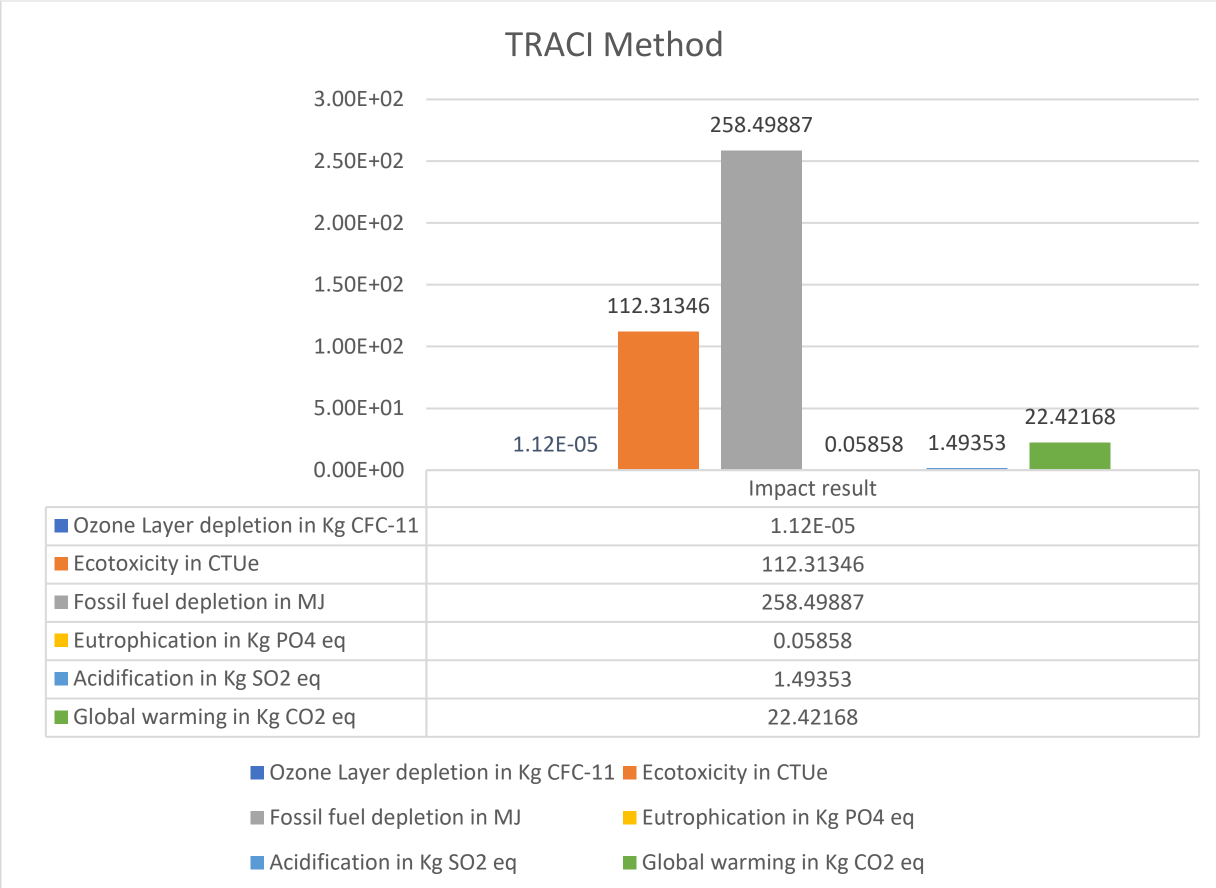
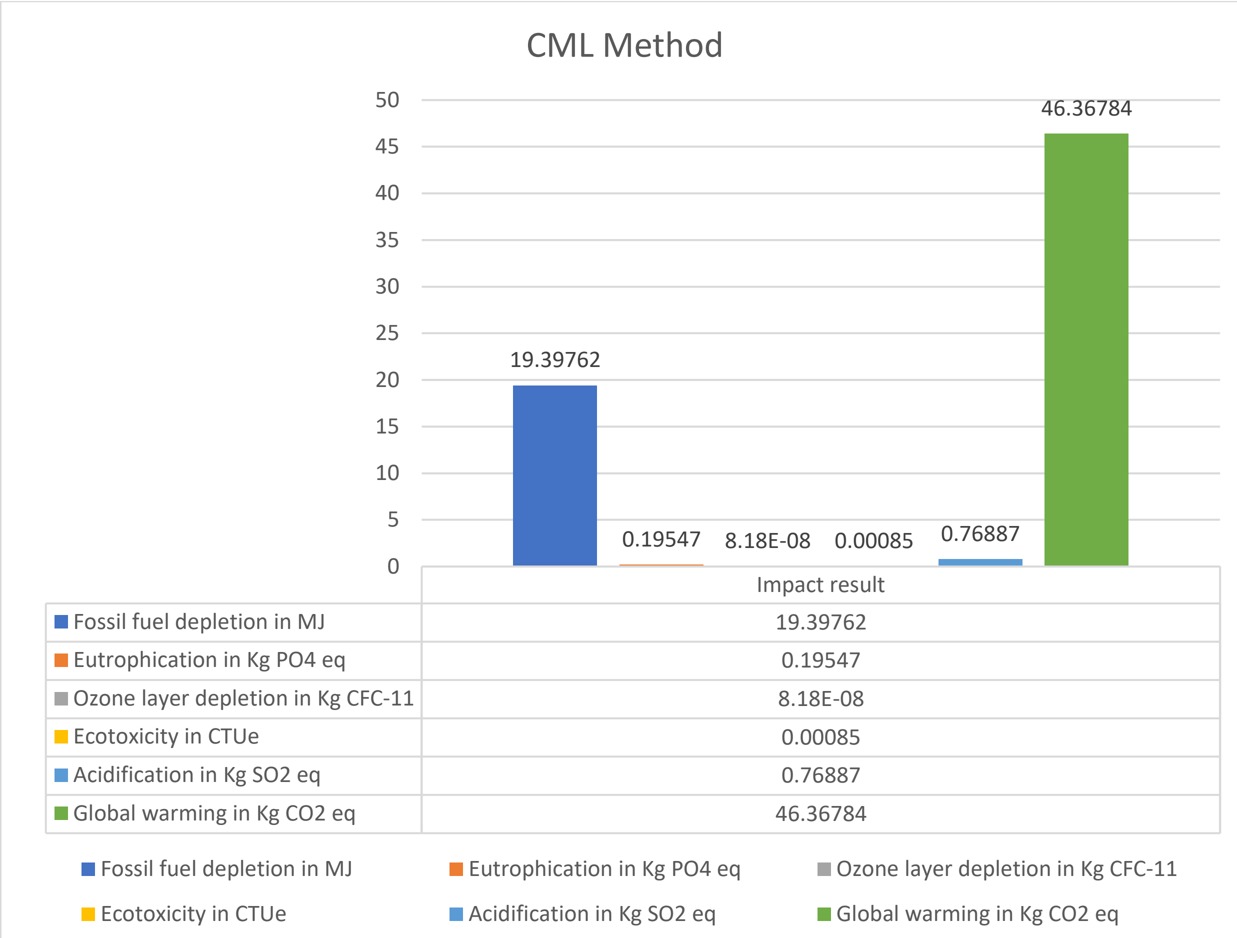


Figure 11: potential impacts of incineration in TRACI method

Some of the most important conclusions from the CML technique are validated by the TRACI method's study of the effect results for incineration. In particular, burning has a little effect on eutrophication and ozone layer depletion but significantly increases ecotoxicity, acidification, fossil fuel depletion, and global warming. These findings highlight the significance of taking into account a variety of environmental effect categories when evaluating the viability of incineration as a waste management strategy. Even though it might have advantages in some areas, including a lower propensity for eutrophication, it also presents serious environmental problems, especially in terms of ecotoxicity and greenhouse gas emissions. Thus, in order to reduce the environmental impact of incineration operations, thorough study and mitigation techniques are necessary.

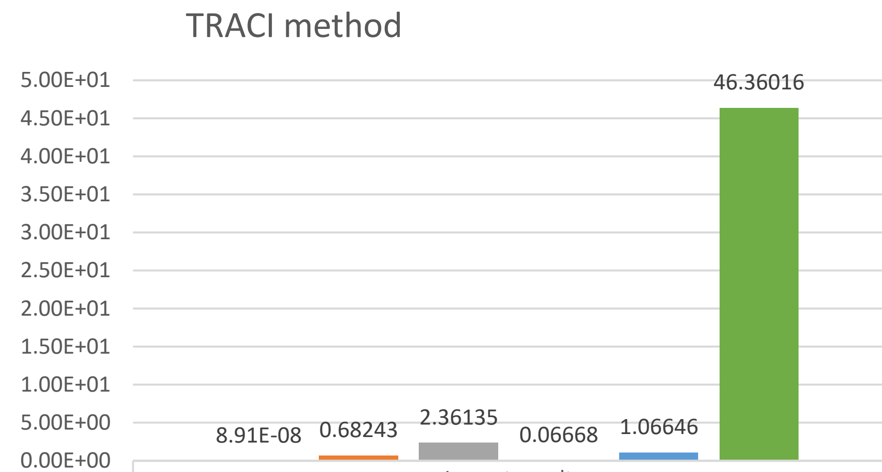
4.6.2 Environmental impacts of Anaerobic Digestion



	Impact result
Fossil fuel depletion in MJ	19.39762
Eutrophication in Kg PO4 eq	0.19547
Ozone layer depletion in Kg CFC-11	8.18E-08
Ecotoxicity in CTUe	0.00085
Acidification in Kg SO2 eq	0.76887
Global warming in Kg CO2 eq	46.36784

Figure 12: Potential impacts of Anaerobic digestion in CML method

The CML method's investigation of the effect outcomes for anaerobic digestion raises a number of important considerations. The effects of anaerobic digestion on terrestrial ecotoxicity, eutrophication, abiotic depletion, and ozone layer depletion seem to be rather minor. Nevertheless, because of methane emissions in particular, it continues to significantly contribute to global warming and acidification. This analysis emphasizes how crucial it is to weigh anaerobic digestion's environmental benefits and drawbacks when assessing how sustainable it is as a waste management solution.



	Impact result
Ozone depletion potential in Kg CFC-11	8.91E-08
Ecotoxicity on CTUe	0.68243
Fossil fuel depletion in MJ	2.36135
Eutrophication in Kg PO4 eq	0.06668
Acidification in Kg SO2 eq	1.06646
Global Warming in Kg CO2 eq	46.36016

Figure 13: Potential impacts of Anaerobic digestion in TRACI method

Both beneficial and detrimental environmental factors are highlighted by the TRACI method's study of the anaerobic digestion impact data. When compared to certain other waste management techniques, anaerobic digestion seems to have comparatively little effects on ozone depletion, eutrophication, and ecotoxicity. Nevertheless, because of methane emissions, it continues to considerably contribute to global warming, acidification, and the modest depletion of fossil fuels. This emphasizes how crucial it is to put policies in place to reduce methane emissions and enhance anaerobic digestion processes' overall environmental performance.

In both impact assessment method of CML and TRACI of anaerobic digestion global warming potential is the highest potential impact among other impacts.

4.6.3 Environmental impacts of Landfill gas system

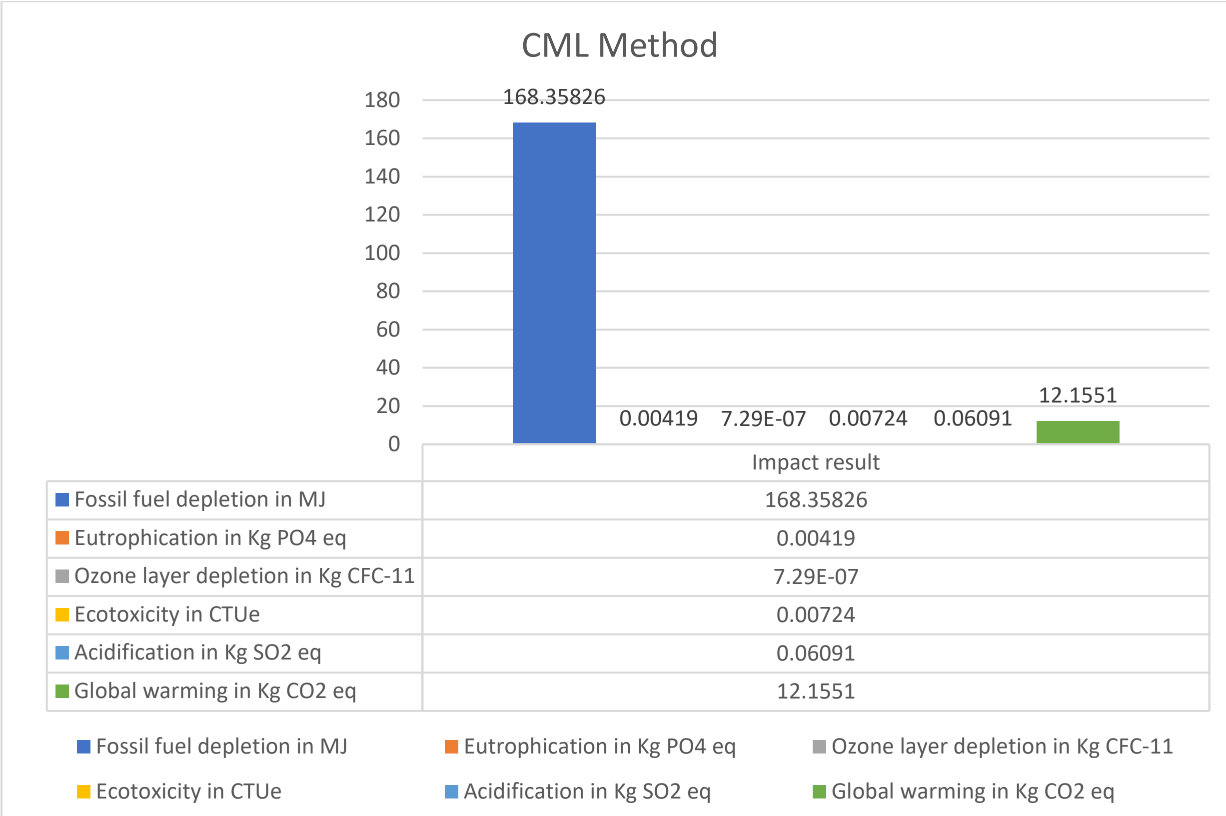


Figure 14: Potential impacts of Landfill gas system in CML method

A number of important conclusions are revealed by the CML method's study of the effect data for landfill gas systems. Landfill gas systems contribute significantly to abiotic depletion, especially in terms of fossil fuels, but have relatively little effect on eutrophication, ozone layer depletion, and terrestrial ecotoxicity. Because of methane emissions, they also have mild effects on global warming and acidification. This emphasizes how critical it is to have policies in place to lessen the negative effects landfill gas systems have on the environment. Some of these policies include increasing the effectiveness of gas capture and encouraging the production of renewable energy from landfill gas.

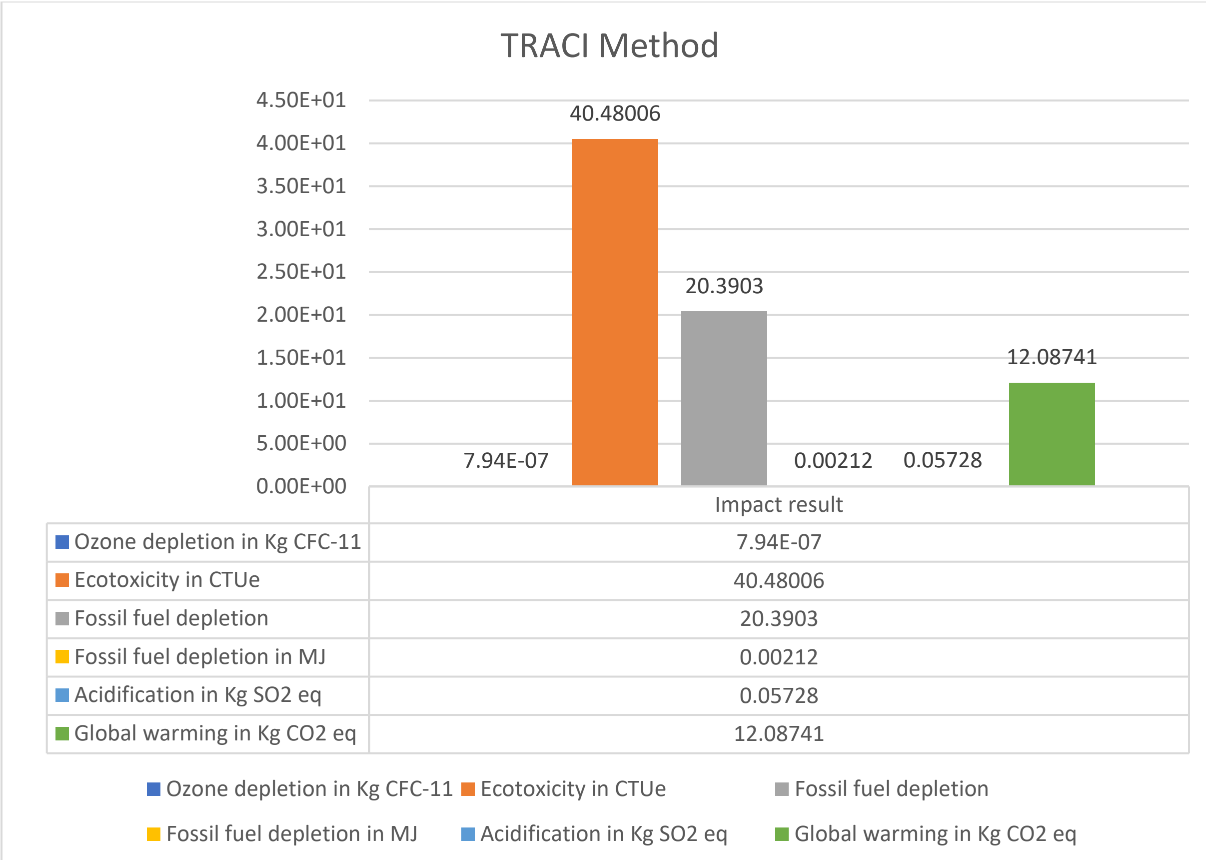


Figure 15: The potential environmental impacts of Landfill gas system in TRACI method

Several significant conclusions are drawn from the TRACI method's analysis of the effect outcomes for landfill gas systems. Landfill gas systems contribute significantly to ecotoxicity, have moderate effects on the depletion of fossil fuels, acidification, and global warming, but have insignificant effects on ozone depletion and small effects on eutrophication. This emphasizes how crucial it is to put in place efficient methods to lessen the negative environmental effects of landfill gas systems, like increasing gas capture efficiency, cutting back on pollution emissions, and encouraging the production of renewable energy from captured landfill gas.

4.6.4 Energy Requirements of Waste to Energy Systems

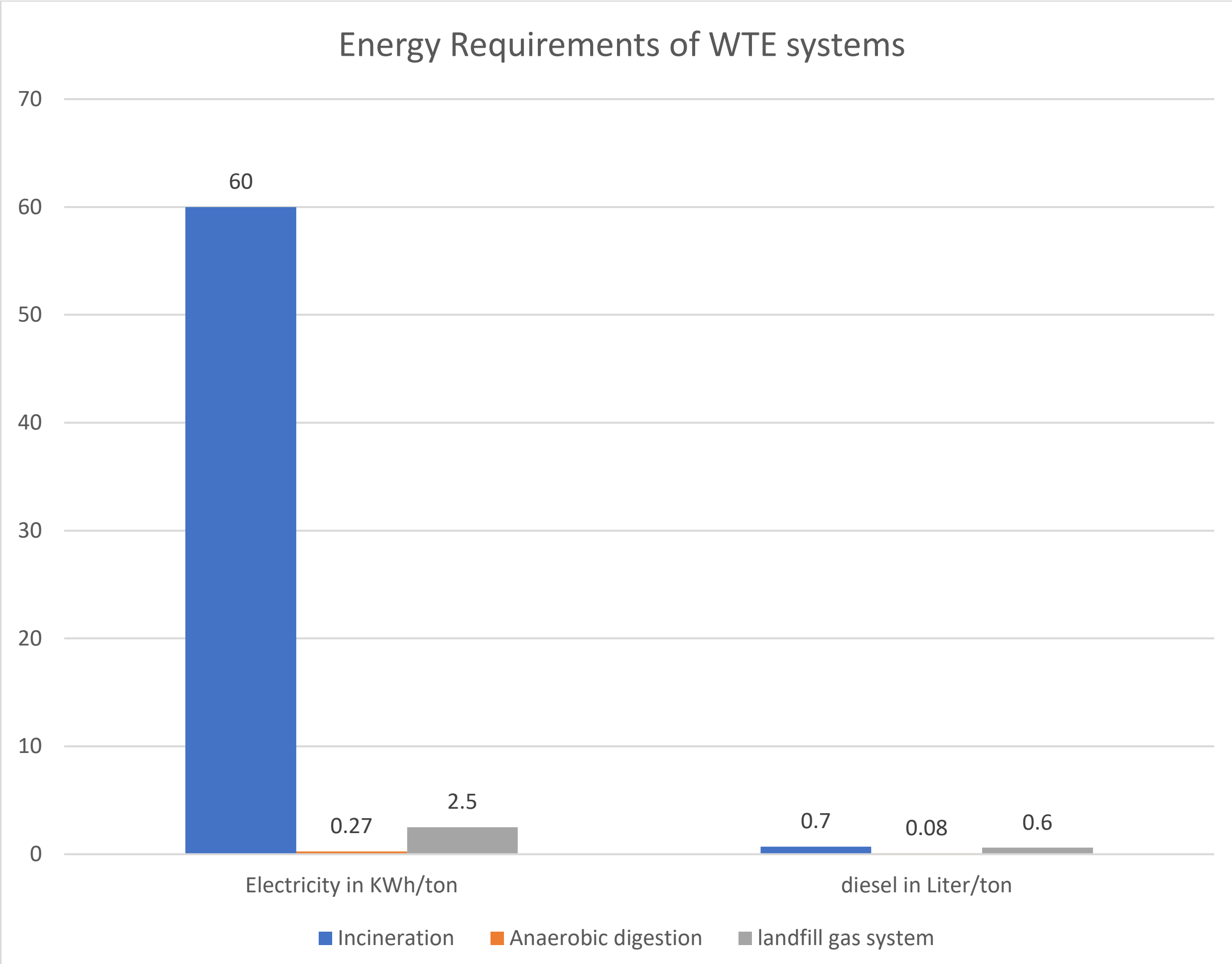


Table 9: Energy requirement by WTE systems

As it is shown incineration has the highest energy requirement due to that there is combustion reaction taking place during the process and also there are many machines that require electricity to work so incineration process require the highest amount of energy among the three WTE systems.

4.6.5 Consistency Check of impact assessment methods

Name	**CML, incineration**	**TRACI, incineration**	**CML, anaerobic digestion**	**TRACI, anaerobic digestion**	**CML, landfill gas**	**TRACI, landfill gas**
Abiotic depletion (fossil fuels)	2516.71922	258.49	19.39762	2.36135	168.3583	20.3903

Eutrophication	0.14816	0.05858	0.19547	0.0668	0.00419	0.00212
Ozone layer depletion (ODP)	1.03E-05	1.13E-05	8.18E-08	8.91E-08	7.29E-07	7.94E-07
Terrestrial ecotoxicity	-0.46976	112.313	0.00085	0.6824	0.00724	40.48006
Acidification	1.41877	1.493	0.76887	1.06646	0.06091	0.05728
Global warming (GWP100a)	22.88428	22.42168	46.36784	46.36784	12.1551	12.08741

Table 10: consistency check of impact assessment methods

CML: The impact of incineration is far greater than that of landfill gas and anaerobic digestion combined.

TRACI: Similar trend, with a greater influence from incineration.

Consistency: Both approaches concur that using fossil fuels has a greater impact than other fuels.

CML: The biggest impact comes from anaerobic digestion, which is followed by incineration and landfill gas.

TRACI: The pattern is a little different, with the largest influence coming from incineration, which is followed by anaerobic digestion and landfill gas.

Consistency: While there is some variation in the techniques' rankings, they both concur that anaerobic digestion has a comparatively greater impact.

Ozone Layer Depletion (ODP): Compared to other waste management techniques, both approaches have extremely little effects.

Consistency: In this category, the minimal impact of both strategies is consistent.

Terrestrial Ecotoxicity in CML: Anaerobic digestion has a substantially smaller impact than incineration and landfill gas.

TRACI: Anaerobic digestion, landfill gas, and incineration have the greatest effects, respectively.

Consistency: Although the rankings differ, both approaches concur that incineration has a greater impact than anaerobic digestion.

Regarding acidification, both techniques largely concur that incineration has the greatest effect, followed by anaerobic digestion and landfill gas.

Consistency: The relative ranking of impacts is displayed consistently by both techniques.

Global Warming (GWP100a): The effects of both approaches are comparatively similar when considering all WTE techniques.

Consistency: Both approaches consistently demonstrate comparable effects between them.

From the consistency check of impact assessment methods of CML and TRACI for incineration scenario there is consistent result in global warming potential, ozone depletion potential and acidification potential. For anaerobic digestion scenario there is consistent result in ozone depletion potential, global warming potential. For landfill gas scenario there is consistent result in global warming potential, acidification potential, ozone depletion potential and approximately eutrophication potential.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The conducted research has explored the complex field of waste-to-energy systems, concentrating on the anaerobic digestion, landfill gas systems, and incineration processes in relation to the CML and TRACI impact assessment methods.

In this study the researcher collected solid waste sample from selected kebeles from all the six sub cities of Bahir Dar town to conduct life cycle inventory analysis of waste to energy. Then then waste samples are further characterized by proximate analysis to determine their moisture content, ash content fixed carbon content and lower heating value. These data are important in life cycle inventory analysis. The statistical data analysis was carried out in python statstical library scipy.

The life cycle impact assessment was done in a software tool known as Openlca using impact assessment methods CML and TRACI. while incineration has a large potential for producing energy and reducing waste volume, it has limitations in environmental impacts.

Based on the impact assessment results incineration has most environmental impacts in impact categories of fossil fuel depletion, ozone depletion potential, acidification potential. Whereas, anaerobic digestion has environmental impacts of global warming potential and eutrophication potential. The least number of environmental impacts are associated with landfill gas management.

Based on energy requirement incineration has highest amount of energy requirement followed by landfill gas system. Anaerobic digestion has the least amount of energy intake.

In consistency check of impact assessment method results of CML and TRACI global warming potential, ozone depletion potential and acidification potential for incineration and landfill gas system whereas, for anaerobic digestion the consistent results are shown in global warming potential and ozone depletion potential.

5.2 Recommendation

The following recommendations have been made

- The present is done using OpenLca software tool but other researches are recommended to use another LCA software to get comprehensive knowledge about waste to energy system environmental impacts.
- Develop LCA databases in universities and in other stakeholders to assess and predict environmental burdens of products, systems or projects.
- Make life cycle assessment part of planning before installing any factories, systems or projects.
- Further researches are needed in techno-economic analysis of waste to energy systems to get comprehensive information about waste to energy systems.
- Studies are needed in another waste to energy systems and their environmental impacts like pyrolysis, gasification, membrane bio reactor e.t.c.

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APPENDIX 1

Waste category	Day 1	Day 2	Day 3	Day 4	Day 5	day 6
Food waste	54.5	59.3	63.5	51.4	60	56.6
Plastic	5.34	4.5	7.1	5.7	4.9	6
Paper and Cardboard	9.89	7.5	5	4	6	7.2
Textile	4.8	2.6	5.3	3.2	4	2
Glass	0.65	0.8	1	0	0.5	1.4
Metals	0.93	0.5	0.9	1.2	1	0.8
Yard	23.89	24.8	17.2	34.5	23.6	26

Table 11: MSW composition of Dagmawi Menelik sub city Midre Genet kebele

Waste category	Day 1	Day 2	Day 3	Day 4	Day 5	day 6
Food waste	62.1	49.4	56.6	64.3	60.8	58.2
Plastic	5.2	6.2	5.8	7	4.4	4.2
Paper and Cardboard	7.8	10.1	9.4	8.8	10.5	9.8

Textile	2.5	4.3	3	3.5	4	2
Glass	0.8	2.1	1.2	1	0.7	0.9
Metals	1.1	1.4	1.3	0.9	1.2	1.5
Yard	20.5	26.5	22.7	14.5	18.4	23.4

Table 12: MSW composition of Dagmawi Menelik sub city Finote kebele

Waste category	Day 1	Day 2	Day 3	Day 4	Day 5	day 6
Food waste	54	61.5	63.2	49.8	57.9	60
Plastic	4.8	5.7	3.4	9	4.2	7
Paper and Cardboard	12.5	11	13.4	9.6	8.5	10.3
Textile	3	2.6	1.9	4.2	2.9	2.1
Glass	0.7	0.3	0.5	1.2	0	0
Metals	0	0	0.7	0.2	0	0.3
Yard	25	18.9	16.9	26	26.5	20.3

Table 13: MSW composition of Dagmawi Menelik sub city Addis Amba kebele

Waste category	Day 1	Day 2	Day 3	Day 4	Day 5	day 6
Food waste	48.7	51	43.1	44.07	46.3	39.6
Plastic	6.4	8	10.23	9.3	5.9	11.4
Paper and Cardboard	10.21	6.9	13.2	11.7	9.45	14.2
Textile	2.8	3.8	5	4.8	1.7	1.8
Glass	5.4	4.4	6	0	3.6	2.7
Metals	1.1	0.65	1.3	0.97	1	0
Yard	25.39	25.25	21.17	29.16	32.05	30.3

Table 14: MSW composition of Fasilo sub city 01 kebele

Waste category	Day 1	Day 2	day 3	Day 4	Day 5	day 6
Food waste	44	49	52	58.5	41	54.6
Plastic	9.8	10.2	6.7	7.9	12.3	4.6
Paper and Cardboard	13.1	11	8.2	10.4	9	8.6

Textile	2.3	3	1.4	4	1.1	3.5
Glass	1.4	3.2	2	1.8	0	0.3
Metals	2	1.2	2.4	1	3	0.8
Yard	27.4	22.4	27.3	16.4	33.6	27.6

Table 15: MSW composition of Gish Abay sub city Abenet kebele

Waste category	Day 1	Day 2	day 3	Day 4	Day 5	day 6
Food waste	52	58.4	61	54.3	57.5	63.2
Plastic	8.5	6.8	5.5	6.1	4.9	6
Paper and Cardboard	12.4	10.5	11.3	8	7.9	8.2
Textile	3.1	2.9	4.1	1.9	4	3.5
Glass	1.1	0.3	0.8	0.6	1.5	1.4
Metals	1.3	0.6	0	1.2	1	0.8
Yard	21.6	20.5	17.3	27.9	23.2	16.9

Table 16: MSW composition of Gish Abay sub city Hidase kebele

Waste category	Day 1	Day 2	day 3	Day 4	Day 5	day 6
Food waste	69.8	63.6	59.9	60.4	57.9	67.2
Plastic	6.22	6.9	4.8	5.7	6	5.5
Paper and Cardboard	8.6	10.2	8	4	9.4	7.9
Textile	7.4	4	3.3	3.2	2.8	3
Glass	3.66	4.4	5	7	4	0
Metals	0.4	0	1.6	1.4	1.8	0.9
Yard	3.92	10.9	17.4	18.3	18.1	15.5

Table 17: MSW composition of Belay Zeleke sub city 07 kebele

Waste category	Day 1	Day 2	day 3	Day 4	Day 5	day 6
Food waste	61.7	57.4	64	52.4	44.3	63.5
Plastic	5.77	3.66	4	6.88	4.9	6
Paper and Cardboard	8.2	9	6.5	12.5	6	7.2
Textile	3.11	1.8	2.5	1.44	4	7.8

Glass	6.5	3.5	4.5	2.1	0.5	1.4
Metals	0.32	1.4	1.89	0.88	1	0.8
Yard	14.4	23.24	16.61	23.8	23.6	13.3

Table 18: MSW composition of Tana sub city Midre Genet kebele

Waste category	Day 1	Day 2	day 3	Day 4	Day 5	day 6
Food waste	55.8	62.3	60	58.4	53.9	57.7
Plastic	6.2	4.4	8	6.8	5.7	5
Paper and Cardboard	10.6	7.5	6.5	11.3	9	9.2
Textile	4.1	3.4	2.9	1.9	3.2	5.1
Glass	0	1.4	1.7	0.3	0.8	1
Metals	0	0	0.5	1.2	0.6	0.4
Yard	23.3	21	20.4	20.1	26.8	21.6

Table 19: MSW composition of Tana sub city Ras Agez kebele

Waste category	Day 1	Day 2	day 3	Day 4	Day 5	day 6
Food waste	61	55.8	68.2	52.1	56	69
Plastic	5.4	6	4.5	7.2	4	3.8
Paper and Cardboard	11	7.5	8	9.1	13.4	10.5
Textile	3	2.1	1.9	2.5	5	4.2
Glass	1.1	0	0	0.8	0.3	0.9
Metals	0	0	0.3	1.5	0	0.7
Yard	18.5	28.4	17.1	26.8	21.3	10.9

Table 20: MSW composition of Tana sub city Shimbit kebele

Waste category	Day 1	Day 2	day 3	Day 4	Day 5	Day 6
Food waste	48.5	51	44	52.5	55	57
Plastic	8.5	10	6.8	5.9	9.2	7.9
Paper and Cardboard	7	6.6	4.5	4	11.3	6
Textile	3.5	4	2.6	2	3.2	3.3
Glass	0.5	1.3	0.6	0	1	2.2

Metals	1	1.2	3	1.8	2.5	1.4
Yard	31	25.9	38.5	33.8	17.8	22.2

Table 21: MSW composition of Atse Tewodros sub city Maraki kebele

Waste category	Day 1	Day 2	day 3	Day 4	Day 5	Day 6
Food waste	55.3	59.7	62.5	57.6	61	58
Plastic	6.5	7.7	3.9	5.6	8.2	6.2
Paper and Cardboard	8.2	6.6	11.3	6.7	10	7.9
Textile	3.1	2.3	4	3.5	3.2	2.9
Glass	0	1.1	0.4	0	1.3	1.7
Metals	0.6	1	0.5	0	0.8	1.4
Yard	26.3	21.6	17.4	26.6	15.5	21.9

Table 22: MSW composition of Atse Tewodros sub city Abay Ras kebele

Waste category	Day 1	Day 2	day 3	Day 4	Day 5	Day 6
Food waste	61.5	56.2	65	51.9	61	55.9
Plastic	5.2	4.7	6	4.2	7.2	5.8
Paper and Cardboard	11	9.5	13	8.7	9.8	10
Textile	1.8	3	5.1	2.7	4.2	2.5
Glass	0.6	0.2	1.1	0.8	1	0
Metals	0	0.9	0.5	1.4	0.8	0
Yard	19.9	25.5	9.3	30.3	16	25.8

Table 23: MSW composition of Atse Tewodros sub city Addis Alem kebele

APPENDIX 2

Source code of data analyzed in python python

```
import random

# List of kebeles in Bahir Dar

Dagmawi_menelik = [“midre_genet”, “selam”, “addis_amba”,”marzeneb”,”finote”]


# Number of kebeles to sample
```

```
num_kebeles_to_sample = 3

# Randomly sample kebeles
random_sampled_kebeles = random.sample(kebeles, num_kebeles_to_sample)

print("Randomly sampled kebeles in Bahir Dar:")
for kebele in random_sampled_kebeles:
   print(kebele)
```

```
import random
# List of kebeles in Bahir Dar
Fasilo = [“01”, “02”, “03”, ”04”]

# Number of kebeles to sample
num_kebeles_to_sample = 1
random_sampled_kebeles = random.sample(kebeles, num_kebeles_to_sample)

print("Randomly sampled kebeles in Bahir Dar:")
for kebele in random_sampled_kebeles:
   print(kebele)

import random
# List of kebeles in Bahir Dar
Gish_abay = [“abnet”, “ghion”, “selam_ber”,”hidasefour”]
```

```
# Number of kebeles to sample
num_kebeles_to_sample = 2

# Randomly sample kebeles
random_sampled_kebeles = random.sample(kebeles, num_kebeles_to_sample)

print("Randomly sampled kebeles in Bahir Dar:")
for kebele in random_sampled_kebeles:
    print(kebele)
```

```
import random
# List of kebeles in Bahir Dar
Belay_zeleke = [“seven”, “hagereselam”, “bisrat”]

# Number of kebeles to sample
num_kebeles_to_sample = 1

# Randomly sample kebeles
random_sampled_kebeles = random.sample(kebeles, num_kebeles_to_sample)

print("Randomly sampled kebeles in Bahir Dar:")
for kebele in random_sampled_kebeles:
    print(kebele)

import random
# List of kebeles in Bahir Dar
```

```
Tana = [“midre_genet”, “rasagez”, “shimbit”,”bahta”,”hidase”]

# Number of kebeles to sample
num_kebeles_to_sample = 3

# Randomly sample kebeles
random_sampled_kebeles = random.sample(kebeles, num_kebeles_to_sample)

print("Randomly sampled kebeles in Bahir Dar:")
for kebele in random_sampled_kebeles:
    print(kebele)


import random
# List of kebeles in Bahir Dar
Atse_tewodros = [“maraki”, “abayras”, “teyima”,”ayertena”,”addisalem”]

# Number of kebeles to sample
num_kebeles_to_sample = 3

# Randomly sample kebeles
random_sampled_kebeles = random.sample(kebeles, num_kebeles_to_sample)

print("Randomly sampled kebeles in Bahir Dar:")
for kebele in random_sampled_kebeles:
    print(kebele)
```

Kruskal Wallis Test

```
from scipy.stats import kruskal
```

```
# Data
Dagmawi_menelik = [58.05, 7.42, 11.96, 3.30, 1.07, 1.04, 22.97]
Fasilo = [45.46, 8.53, 10.94, 3.31, 3.68, 0.83, 27.22]
Gish_abay = [53.59, 7.44, 9.88, 2.90, 1.20, 1.27, 23.5]
Belay_zeleke = [63.13, 5.85, 8.01, 3.95, 4.01, 1.01, 14.02]
Tana = [58.52, 5.45, 9.05, 3.33, 1.48, 0.63, 20.61]
Atse_tewodros = [56.31, 6.63, 8.44, 3.16, 0.76, 1.04, 23.62]

# Perform Kruskal-Wallis test
statistic, p_value = kruskal(Dagmawi_menelik, Fasilo, Gish_abay, Belay_zeleke, Tana, Atse_tewodros)

# Compute ranks
all_data = Dagmawi_menelik + Fasilo + Gish_abay + Belay_zeleke + Tana + Atse_tewodros
all_ranks = [sorted(all_data).index(x) + 1 for x in all_data]

# Calculate mean ranks for each group
mean_ranks = []
for data in [Dagmawi_menelik, Fasilo, Gish_abay, Belay_zeleke, Tana, Atse_tewodros]:
    ranks = [all_ranks[all_data.index(x)] for x in data]
    mean_ranks.append(sum(ranks) / len(ranks))

# Calculate sum of ranks for each group
sum_ranks = [sum([all_ranks[all_data.index(x)] for x in data]) for data in [Dagmawi_menelik, Fasilo,
Gish_abay, Belay_zeleke, Tana, Atse_tewodros]]

# Print results
print("Kruskal-Wallis Test:")
print("Test Statistic:", statistic)
```

```
print("p-value:", p_value)
print("Mean Ranks:", mean_ranks)
print("Sum of Ranks:", sum_ranks)

alpha = 0.05
if p_value < alpha:
    print("There are significant differences in waste composition between subcities.")
else:
    print("There are no significant differences in waste composition between subcities.")
```

Kruskal-Wallis Test:

Test Statistic: 0.27719379485991513

p-value: 0.9980501378898647

mean rank: 21.428571, 23.0, 21.5714, 22.28574, 20.71428, 19.85714

sum of rank: 150, 161, 151, 156, 145, 139

There are no significant differences in waste composition between subcities.

One-way ANOVA

```
from scipy.stats import f_oneway
Dagmawi_menelik = [58.05, 7.42, 11.96, 3.30, 1.07, 1.04, 22.97]
Fasilo = [45.46, 8.53, 10.94, 3.31, 3.68, 0.83, 27.22]
Gish_abay = [53.59, 7.44, 9.88, 2.90, 1.20, 1.27, 23.5]
Belay_zeleke = [63.13, 5.85, 8.01, 3.95, 4.01, 1.01, 14.02]
Tana = [58.52, 5.45, 9.05, 3.33, 1.48, 0.63, 20.61]
Atse_tewodros = [56.31, 6.63, 8.44, 3.16, 0.76, 1.04, 23.62]
```

```
f_statistic, p_value = f_oneway(Dagmawi_menelik, Fasilo, Gish_abay, Belay_zeleke, Tana,
Atse_tewodros)

print("F-statistic:", f_statistic)

print("p-value:", p_value)


# Interpret the p-value

alpha = 0.05

if p_value < alpha:

    print("There are significant differences between group means.")

else:

    print("There are no significant differences between group means.")

F-statistic: 0.0022659383791497566

p-value: 0.9999992000936819

There are no significant differences between group means.
```