

**KWAME NKURUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY**

**COLLEGE OF ENGINEERING**

**FACULTY OF MECHANICAL AND CHEMICAL ENGINEERING**

**DEPARTMENT OF CHEMICAL ENGINEERING**



**LIFE CYCLE ASSESSMENT OF ELECTRICITY PRODUCTION FROM  
ANAEROBIC DIGESTION OF MUNICIPAL SOLID WASTE IN GHANA: A CASE  
STUDY OF ATWIMA NWABIAGYA MUNICIPALITY**

**BY**

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## DECLARATION OF AUTHORSHIP

I hereby declare that this study was conducted by me under the supervision of Dr Patrick Boakye and Dr Mizpah Ama Dziejzorm Rockson. This work has never been submitted to any other institution by anyone for any award. All references cited in this work have been duly acknowledged and I take full responsibility for any shortcomings associated with this work.

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## ABSTRACT

Ghana relies heavily on fossil fuels for energy generation. This dependence on fossil fuels not only burdens the economy but also prevents the exploitation of the country's indigenous renewable energy resources. Anaerobic digestion (AD) is one of the promising waste-to-energy technologies that has great potential for generating clean energy while solving waste management problems in Ghana. A life cycle assessment (LCA) is needed to understand the overall environmental impact of waste-to-energy technologies and to implement future alternatives sustainably. This study applied an LCA to assess the inventory results of a hybrid waste-to-energy plant in the Atwima Nwabiagya Municipality in Ghana and its impact on the environment, including greenhouse gas emissions and energy generation. The study revealed that the anaerobic digestion plant will generate 805,574 kWh/year of electricity, equivalent to 352,589 Nm<sup>3</sup>/year of biogas, from 8,615 tons of municipal solid waste. The life cycle inventory further indicated that greenhouse gas emissions, including CH<sub>4</sub> (3,786.8 kg), NO<sub>x</sub> (1,614.48 kg), and N<sub>2</sub>O (12.79 kg), are produced, which contribute to the overall carbon footprint. Environmental benefits were observed in 10 out of 11 impact categories in the CML-IA baseline method, except for abiotic depletion, which recorded an environmental burden. Contribution analysis revealed that the transport of waste to the plant site was the highest contributor to the environmental impact of the anaerobic digestion system. Scenario analysis suggested that replacing solar PV electricity with Ghana's electricity production mix (2018) leads to a substantial reduction in the abiotic depletion category (-99.61%) but results in increased burdens, notably in acidification (725%). The uncertainty analysis showed that data reliability and temporal correlation play significant roles in quantifying uncertainty. The study concluded that anaerobic digestion is a viable waste-to-energy technology in Ghana that can reduce greenhouse gas emissions and generate renewable energy, but further improvements are needed to optimize its environmental performance and reduce its resource consumption.

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## LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
CH <sub>4</sub>	Methane
CHP	Combined Heat and Power Plant
CO <sub>2</sub>	Carbon Dioxide
CSTR	Continuous Stirred Tank Reactor
CML-IA	Centre of Environmental Science - Impact Assessment
GHG	Greenhouse gases
GJ	Giga Joules
GWh	Giga Watts hour
INC	Incineration
ISO	International Standard Organization
kWh	Kilo Watts hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MSW	Municipal Solid Waste
MT	Metric Tonnes
NO <sub>x</sub>	Nitrogen Oxides
N <sub>2</sub> O	Dinitrogen Oxide
OFMSW	Organic Fraction of Municipal Solid Waste
PV	Photovoltaic
W2E	Waste-to-Energy

## CHAPTER ONE

### INTRODUCTION

#### 1.1 Background of the study

There is a global convergence on the need to promote sustainability in the use and management of resources available to humanity (Demirel and Kesidou, 2019; Lam *et al.*, 2020). Sustainable practices are important for both environmental and economic reasons because they help to reduce waste and conserve resources (Zhang *et al.*, 2021). Goal 12 of the sustainable development goals (SDGs) put forward by the United Nations (UN) calls for a more conscientious approach to consumption and production. On waste management, the UN aims to manage all forms of waste responsibly and environmentally friendly by 2020 (United Nations, 2022). It is apparent then that proper waste management is essential for promoting sustainability. By collecting, treating, and disposing of waste responsibly and efficiently, we can reduce its negative impact on the environment.

Globally, population density increases the generation of solid waste rapidly, along with urbanization, economic growth, and industrialization (Lissah *et al.*, 2021; Misganaw and Teffera, 2021).

Every day, Ghanaians generate about 22,500 tons of waste, with organic waste accounting for roughly 60% of the total (Debrah *et al.*, 2022). The per capita waste generation is 0.47kg/person/day in 2015 (Miezah *et al.*, 2015). Waste generated in 2016 contributed 3.2 million metric tons (MT) of CO<sub>2</sub> which is 8% of the total greenhouse gas (GHG) emissions (Environmental Protection Agency, 2019; World Bank, 2020).

Waste management practices can help to reduce greenhouse gas emissions and combat climate change (Kanhai *et al.*, 2021). Several green technologies have been recommended for organic waste management including composting (aerobic digestion), incineration, and anaerobic

digestion (AD) (Mahajan *et al.*, 2019; Adanu, Gbedemah and Attah, 2020). These waste management techniques are well-established and practiced in most developed countries (Mahajan *et al.*, 2019). However, Ghana amongst other developing nations has a poor waste management strategy (Adanu, Gbedemah and Attah, 2020). Landfills are rarely engineered where available, and other treatment systems are not properly managed (Adanu, Gbedemah and Attah, 2020). Although some waste management facilities do exist in the country, an assessment of the environmental impact of their operations has not been conducted (Afrane *et al.*, 2021). Anaerobic digestion as a waste management technique has proven to be useful in converting organic waste into products such as biogas and digestate that have a positive impact on society with fewer environmental effects (Kumar and Samadder, 2020). The life cycle assessment (LCA) tools are well-built to holistically assess the environmental impacts of products and processes and to propose solutions to meet ecological needs (Nabavi-Pelesaraei *et al.*, 2019).

## **1.2 Problem Statement**

Ghana faces a serious challenge of managing its municipal solid waste (MSW), which is estimated at 22,500 tons per day, with organic waste accounting for about 60% of the total (Debrah *et al.*, 2022). MSW generated yearly in Ghana are poorly disposed of or burnt, which causes pollution and emission of greenhouse gases (GHGs). On the other hand, Ghana suffers from recurrent electricity shortages and heavy dependence on fossil fuels for energy generation, which threaten its energy security and economic development (Bensah *et al.*, 2014; Sakah *et al.*, 2017; Gyamfi *et al.*, 2018; Obeng-Darko, 2019).

Therefore, there is a need to explore alternative and sustainable sources of energy that can address both the waste management and energy generation problems in Ghana. One of these sources is biogas, which can be produced from organic waste through anaerobic digestion. Several small-scale biogas digesters are currently in operation in Ghana, making it the most

widely used technology for managing organic waste, particularly sewage (Ofori-boateng, Teong and Mensah, 2013).

There are inadequate LCA studies on anaerobic digestion in Ghana, where the technology has great potential for addressing waste management and energy generation challenges (Khandelwal *et al.*, 2019; Iqbal, Liu and Chen, 2020; Zhang *et al.*, 2021). Although there are several studies on LCA involving MSW, the source and nature of MSW results in varying impact categories. Galgani, van der Voet and Korevaar, (2014) contributed to climate change mitigation through LCA of anaerobic digestion in Northern Ghana. However, the study did not address several impact categories such as eutrophication, acidification, and human toxicity potentials.

Therefore, there is a need for more comprehensive and context-specific LCA studies on anaerobic digestion in Ghana, where the technology is gaining popularity among small-scale users (Ofori-boateng, Teong and Mensah, 2013; Cudjoe and Mensah, 2021). Such studies can help identify the environmental hotspots and opportunities of anaerobic digestion systems in Ghana and provide guidance for improving the technology and promoting its sustainable adoption.

### **1.3 Justification**

LCA is needed to understand the overall environmental impact of waste-to-energy technologies and to sustainably implement future alternatives (Evangelisti *et al.*, 2014; Gopal *et al.*, 2020). Studies have revealed that MSW, when used as a primary feedstock in waste-to-energy technologies (W2E), is one of the best ways to produce predictable and quantifiable energy while solving environmental challenges (Ayodele, Ogunjuyigbe and Alao, 2017; Lissah *et al.*, 2021). AD as a promising waste-to-energy technology can generate clean energy while reducing waste volume and GHG emissions (Afrane *et al.*, 2021; Cudjoe and Mensah, 2021).

A hybrid waste-to-energy pilot plant has been commissioned at Atwima Nwabiagya Municipality in the Ashanti Region of Ghana to address the waste management and electricity concerns concurrently. There is therefore the need to evaluate the environmental performance and trade-offs of the AD systems using a comprehensive and context-specific life cycle assessment (LCA). Since previous LCA studies on AD in Ghana focused on GHG emissions as the main impact category (Galgani, van der Voet and Korevaar, 2014; Maepa *et al.*, 2017), other impacts such as eutrophication, acidification, and human toxicity potentials which were excluded would be assessed.

#### **1.4 Aim and Objectives**

This study aimed to estimate the environmental impact of generating electricity from the anaerobic digestion of municipal solid waste generated annually in Ghana.

The specific objectives of this study were as follows:

1. Quantify and compile the inventory for the input and output products of the anaerobic digestion process.
2. Estimate the environmental impact of the anaerobic digestion process using the CML-IA baseline method.
3. Conduct a sensitivity and uncertainty analyses of the impact results using scenario analysis and Monte Carlo simulation.

#### **1.5 Organization of Thesis**

The organization of this thesis is centered on five main chapters. Chapter one introduces the background of the study, the problem statement, the justification for research, and the objectives of the study. Chapter two reviews the relevant literature on the topic. Chapter three explains the research methodology used in the study.

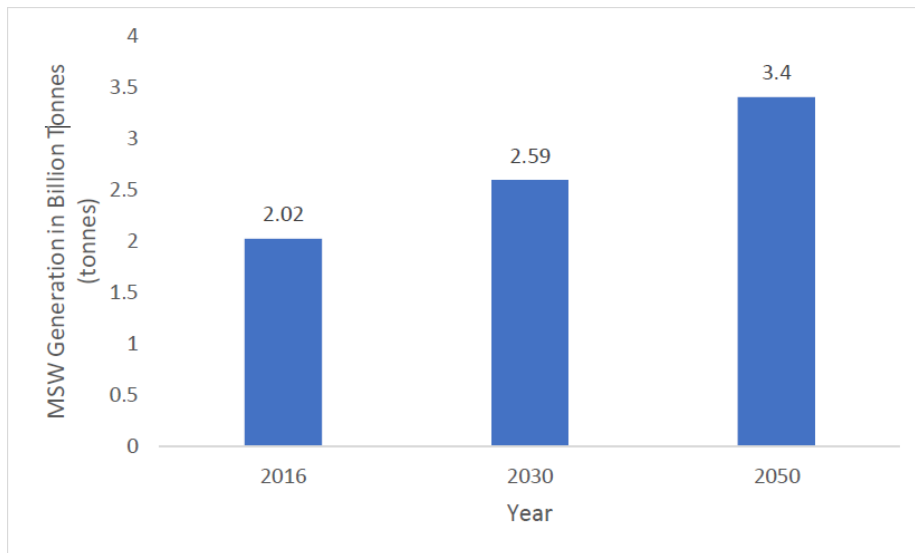
Chapter four analyzes, conceptualizes, and discusses the results obtained in the study. Chapter five concludes the thesis and provides some recommendations based on the research findings.

## CHAPTER TWO

### LITERATURE

#### 2.1 Concept of Municipal Solid Waste

Municipal solid waste can be considered household waste, commercial waste, and other waste that have similar characteristics and composition as household waste (Soltani, Sadiq and Hewage, 2016). It comprises residential, industrial, institutional, commercial, construction, and demolition waste collected and disposed at municipal disposal sites (Hoornweg, Bhada-Tata and Kennedy, 2015). MSW can also be described as a mixture of solid waste dumped as garbage, thrash, and refuse by urban and rural populations (Nanda and Berruti, 2021). It can be inferred from these definitions that municipal solid waste is characterized by the source and composition of waste. Growing population density, urbanization, and economic growth affect the generation of MSW worldwide (Laurent *et al.*, 2014). As the population in a particular area increase, there is a higher demand for goods and services, which directly affects the generation of MSW. Economic growth is also reflected in the improvement of people's standard of living, which leads to an increase in the consumption of goods and services. Owing to the rapid rise in population and urbanization, global waste generation is predicted to rise by 70%, reaching 3.4 billion tons by 2050, as shown in Figure 2. 1. In 2016, MSW generation was 2.02 billion tons, and it will likely reach 2.59 billion tons by 2030 and expand to approximately 3.4 billion tons by 2050 (Chen *et al.*, 2020).



**Figure 2. 1 The Projected Generation of MSW Worldwide from 2016 to 2050 in Billion Tons**

(Source: Chen *et al.*, 2020; Nubi, Morse and Murphy, 2022)

### **2.1.1 Composition of Municipal Solid Waste**

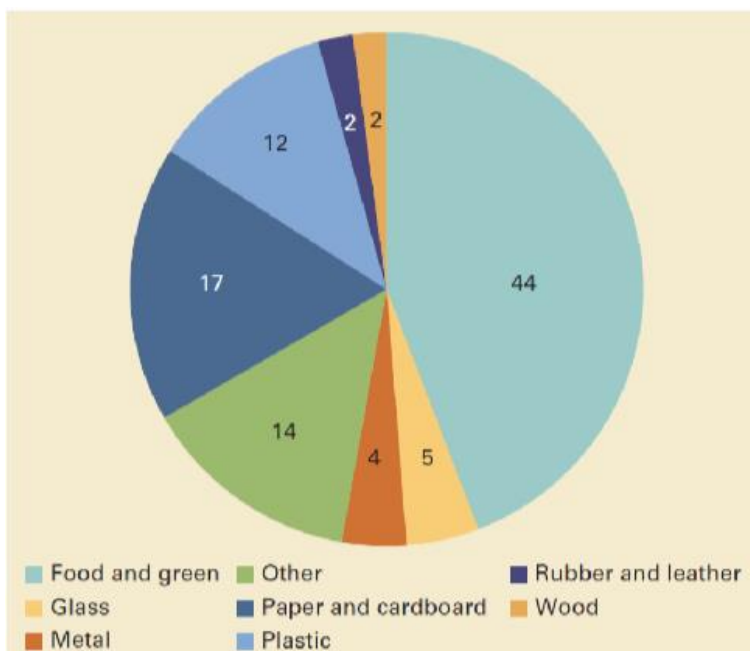
According to Nanda and Berruti, (2021), Municipal Solid Waste (MSW) is generally composed of biodegradable and non-biodegradable substances. Biodegradable fractions include food waste, animal manure, leaf litter, yard waste, paper, and cardboard. They often contain high amounts of cellulose, hemicellulose, proteins, and lipids. The non-biodegradable fractions consist of plastic, glass, metal, rubber, inert materials, and electronic waste. They are often recycled and further treated, as they pose environmental concerns when disposed of.

Studies have shown that the composition of MSW is shifting due to changing consumption patterns (Liu *et al.*, 2019). In developed countries, the amount of paper and cardboard in MSW has decreased, while plastic waste has increased (Liu *et al.*, 2019). This shift can be attributed to the increased use of packaging materials, particularly in the food industry (Mahyari *et al.*, 2022). Similarly, the amount of food waste in MSW has increased due to changes in dietary

habits, such as the increased consumption of pre-packaged food and ready-to-eat meals (Thyberg and Tonjes, 2016).

In developing countries, the composition of MSW differs due to differences in lifestyle, income levels, and waste management practices (Sharma and Sharma, 2020). Organic waste, such as food waste, paper, and cardboard, usually accounts for a higher proportion of the waste stream in developing countries (Sharma and Sharma, 2020). This is partly due to the lower levels of plastic packaging and the higher proportion of organic waste generated by traditional markets and agriculture (Sharma and Sharma, 2020).

The current global municipal solid waste composition illustrated in Figure 2. 2 reveals that organic waste (comprising food, green, and wood wastes) has the highest percentage (46%), and rubber and leather have the lowest percentage composition.



**Figure 2. 2. Global waste composition**

(Source: World Bank, 2018)

### **2.1.2 Municipal Solid Waste Management (MSWM)**

MSWM is the process of direct waste generation, storage, collection, source-separation, processing, transportation, treatment, recovery, and disposal of solid waste, making it harmless to humans, animals, plants, and the environment (Ezechi *et al.*, 2017; Trupti Phapal, 2017).

Solid waste treatment strategies have been developed and widely practised globally to address waste disposal issues. Techniques include landfilling, composting, incineration, and anaerobic digestion. Many European countries have advanced solid waste management systems in operation (Lissah *et al.*, 2021) while developing countries do not have proper waste management strategies.

### **2.1.3 Municipal Solid Waste Situation in Ghana**

Like other developing economies, Ghana is experiencing a rapid increase in waste generation, particularly in urban areas, driven by population growth, urbanization, and industrialization. Each day, an estimated 22,500 tons of waste are generated in Ghana (Debrah *et al.*, 2022). Municipal solid waste (MSW) constitutes the largest portion of the total waste generated, with organic materials accounting for approximately 62% of household MSW (Miezah *et al.*, 2015). The nature and volume of waste are pivotal factors in determining the most suitable energy recovery approach and conducting a cost-benefit analysis for waste management projects. Within urban regions, only 52% of the overall waste generated receives effective collection, whereas the remaining portion is either burned by households, haphazardly dumped in open spaces, or irresponsibly disposed of in water sources (Ofori-boateng, Teong and Mensah, 2013). Although recyclables account for approximately 22% of the waste stream, waste management alternatives, such as recycling and composting, face additional operational costs owing to the limited practice of source-sorting MSW in Ghana (Ofori-boateng, Teong and Mensah, 2013). Relevant government agencies must enforce and implement sanitation laws to address waste management challenges effectively.

The utilization of MSW as a valuable energy source through advanced treatment technologies has garnered significant global attention. Nevertheless, Ghana and other African nations have encountered unique challenges related to the socioeconomic, environmental, and technical aspects of waste management systems. Various feasibility studies have indicated that electricity generation from MSW is highly viable in Ghana, considering the substantial quantity and composition of waste produced (Ofori-boateng, Teong and Mensah, 2013; Kemausuor *et al.*, 2014; Amo-asamoah, Asumadu and Edwards, 2020).

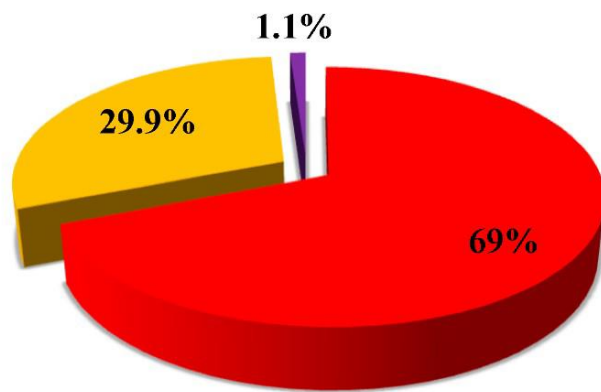
## **2.2 Ghana's energy profile.**

Ghana, one of Africa's fastest-growing economies, has witnessed a steady increase in electricity demand over the years, driven by factors such as economic growth, urbanization, industrialization, and rural electrification (Geiger, Trenczek and Wacker, 2019). In 2020, Ghana had an overall primary energy supply of 12,038 ktoe, a 7.97% increase from the previous year (Energy Commission Ghana 2021). Electricity consumption accounted for 11.54% of the total primary energy supply in the same year (Energy Commission Ghana, 2021). Notably, between 2005 and 2015, Ghana experienced an average annual economic growth of 4.5%, as measured by the gross domestic product (GDP), while electricity consumption witnessed an average yearly growth rate of 9.5% (Geiger et al., 2019, Energy Commission Ghana, 2021). The peak demand for electricity in 2021 was projected to reach 3,304 MW, representing a 6.92% increase compared to the highest demand recorded in 2020 (Energy Commission Ghana, 2021).

However, the growth in electricity demand has not been met with a corresponding increase in the installed capacity within the country. The overall installed electricity generation capacity rose from 5289 MW in 2020 to 5481 MW in 2021 (Energy Commission Ghana, 2021; Ghana Investment Promotion Centre, 2022). It is evident that the installed capacity has only increased by 4.84% considering the 6.92% annual growth in energy demand.

This disparity between demand and supply has resulted in significant challenges, including frequent power outages and complete blackouts (Gyamfi *et al.*, 2018). These power disruptions have had detrimental impacts on Ghana's GDP. Furthermore, despite the government's aim to achieve universal access to electricity by 2020, the existing electricity access rate throughout the nation is currently 87%. This comprises 50% rural inhabitants and 91% urban residents who have been connected to the electricity grid (Energy Commission Ghana, 2021; Ghana Investment Promotion Centre, 2022). These challenges regarding electricity have placed significant pressure on the government and other relevant stakeholders to tackle the prevailing situation.

Recognizing the need for alternative energy sources and the environmental risks associated with conventional energy production, the government of Ghana has identified renewable energy as a viable solution to diversify the energy supply mix, holding great promise for addressing this issue (Agyekum, Ali and Kumar, 2021). In 2016, a target was set under the Renewable Energy Act to achieve a 10% increase in renewable electricity production by the end of 2020 (Energy Commission Ghana, 2019). However, as of December 2019, Ghana had only achieved 0.8% of its renewable energy target. The country's electricity mix has predominantly relied on conventional thermal plants, contributing 69% to the overall installed capacity, while hydroelectric power accounts for 29.9%. Alternative sources of renewable energy, such as solar energy and biomass, represent only a minor share of 1.1% as shown in Figure 2. 3 (Energy Commission Ghana, 2021).



■ Thermal   ■ Hydro   ■ Solar and biomass

**Figure 2. 3 Share of Ghana's installed power capacity by Source in 2020**

(Source: Energy Commission Ghana, (2021) ).

**Table 2. 1 REMP targets for W2E technologies in Ghana (Energy Commission Ghana, 2019)**

Technology/Source		Units	Reference (2015)	2020	2025	2030
<b>Utility-scale power</b>	MSW	MW	0.1	0.1	30.1	50.1
<b>Biogas</b>	Agricultural/Industrial organic waste	Units	10	30	100	200
	Institutional	Units	<100	180	320	500
	Domestic		<50	80	130	200

The need to address Ghana's increasing electricity demand and mitigate the adverse impacts of climate change led to the development of the Renewable Energy Master Plan (REMP) in 2019 (Energy Commission Ghana, 2019). The primary objective of the REMP is to outline a comprehensive roadmap on renewable energy for socioeconomic advancement and environmental sustainability by 2030 (Energy Commission Ghana, 2019). As part of this plan, electricity generation from municipal solid waste (MSW) is projected to reach a capacity of 50.1 MW by 2030, as indicated in Table 2. 1.

The integration of waste-to-energy (W2E) technologies into Ghana's energy mix offers several advantages, as highlighted in the Master Plan (Energy Commission Ghana, 2019). First, by utilizing more stable conversion technologies, the W2E can contribute to increasing the overall power generation capacity. This enhanced capacity can help to meet the growing electricity demand more consistently. Second, W2E facilities can provide a reliable and uninterrupted electricity supply, which is particularly beneficial for industrial applications that require a steady power source. Finally, the integration of W2E can create new employment opportunities, contributing to job creation and socioeconomic development within the country (Energy Commission Ghana, 2019).

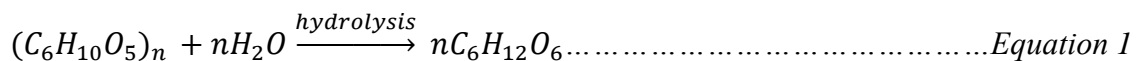
## **2.3 Concept of Anaerobic Digestion**

### **2.3.1 Anaerobic Digestion**

Anaerobic Digestion (AD) is a complex process consisting of a series of biochemical reactions under anoxic conditions using microbes to produce biogas (Aslanzadeh, 2014). At various stages, diverse communities of microorganisms work together to decompose complex biomass polymers and transform them into a mixture of gases (Uddin and Wright, 2022). The anaerobic digestion stages include hydrolysis, acidogenesis, acetogenesis, and methanogenesis as shown in Figure 2. 4 (Uddin and Wright, 2022). Each of these steps plays a crucial role in overall methane production during anaerobic digestion (Aslanzadeh, 2014).

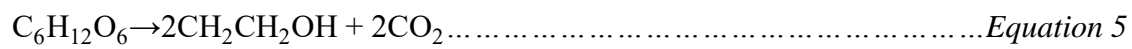
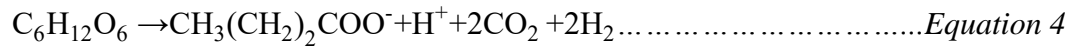
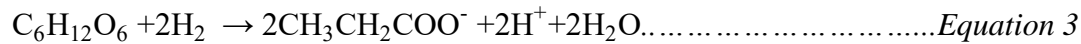
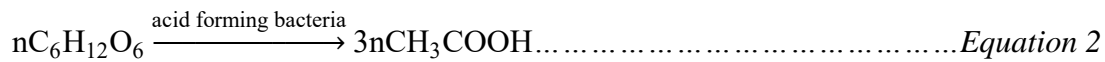
### 2.3.1.1 Hydrolysis

The initial stage of anaerobic digestion involves the enzymatic conversion of insoluble organic materials and complex compounds, including proteins, lipids, fats, polysaccharides, and nucleic acids, into soluble organic materials (Van *et al.*, 2020). These soluble compounds serve as a source of energy and carbon for compounds, such as monosaccharides, amino acids, and other simple organic compounds. This crucial step is facilitated by strict anaerobic microorganisms, such as bactericides, clostridia, and facultative bacteria, such as streptococci (Merlin Christy, Gopinath and Divya, 2014). Hydrolytic microorganisms possess a remarkable ability to withstand environmental variations and potential toxins that might be present in the feedstock (Menzel, Neubauer and Junne, 2020). The hydrolysis of lignocellulosic materials is inherently slow, making it the rate-limiting step in the digestion process (Yang *et al.*, 2010). However, this challenge can be effectively addressed using pretreatment techniques that include physical, chemical, and biological methods (Gahlot *et al.*, 2022). These pretreatment processes have the potential to greatly accelerate the hydrolysis of lignocellulosic materials, facilitating their efficient digestion (Krishna and Kalamdhad, 2014; Zhang *et al.*, 2014).



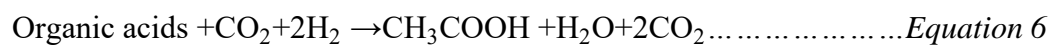
### 2.3.1.2 Acidogenesis/fermentation

The second step in the reaction was acidogenesis. Acidogenic bacteria convert simple monomers into organic acids, primarily volatile fatty acids (VFAs), hydrogen, and carbon dioxide. The type of feedstock, bacteria, and external conditions, such as hydrogen partial pressure and pH, have a significant impact on these products. The optimum pH range frequently reported for optimal conditions is 5.5 to 6.5 (Mao *et al.*, 2015). This stage is referred to as fermentation. A detailed illustration of the acidogenesis process is given in equations 2–5.



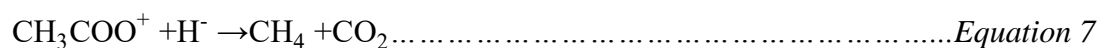
### 2.3.1.3 Acetogenesis

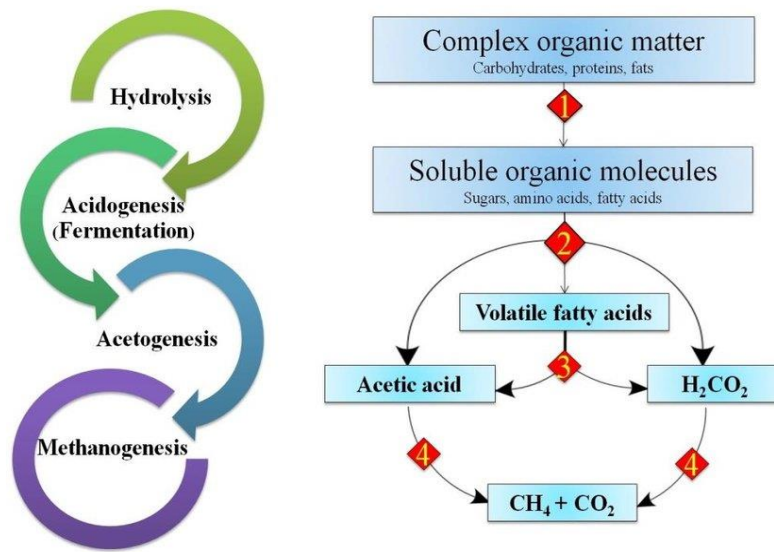
Acetogenesis is the third step of the Anaerobic process. During this stage, volatile fatty acids are further converted into acetic acid, carbon dioxide, and hydrogen gas (Bajpai, 2017). These reactions are performed in the presence of carbon dioxide and hydrogen, which were produced in the previous stage. Acetogenic bacteria can use a variety of organic acids as substrates, including lactic, propionic, and butyric acids. The acetogenesis reaction is described by Equation 6:



### 2.3.1.4 Methanogenesis

The final step of anaerobic digestion involves the conversion of acetate into methane and carbon dioxide, which consumes hydrogen gas. Microbes, also known as methanogens, are responsible for producing biogas (Donoso-Bravo *et al.*, 2009). The decomposition of acetate by methanogens is represented in equation 7 whereas equation 8 illustrates the production of methane by using hydrogen and carbon dioxide.





**Figure 2. 4 Flow chart of the anaerobic digestion process**

(Source: Benali, Hamad and Hamad, (2019) )

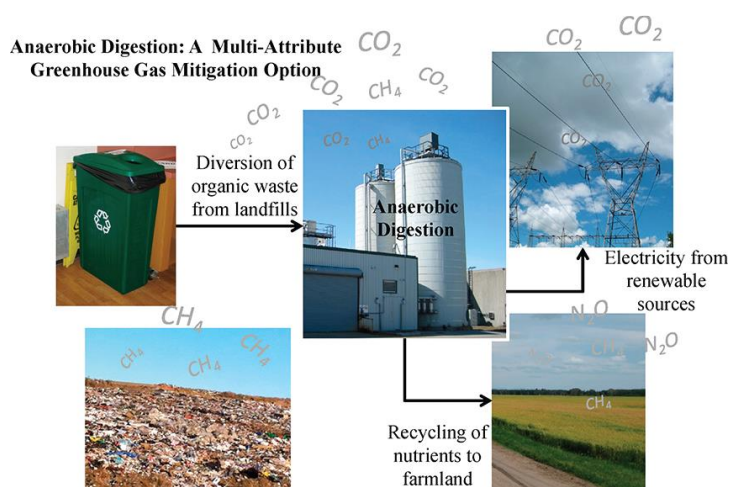
## 2.4 Applications of Biogas

Some applications of biogas include use as cooking fuel, generation of electricity, and upgrading to biomethane for use as electric fuels. Biogas, like other light gases from petrochemicals and natural gas, has a high calorific value of methane. Cooking fuels used in Ghana are sourced from charcoal, firewood, biogas, and liquefied petroleum gas (LPG). Biogas is not used much in Ghana compared to other cooking fuels. They can be used as an alternative to LPG as cooking fuel for household use (Afrane and Ntiamoah, 2011).

Biogas can be fed into an internal combustion engine that drives a generator, producing electricity that may be utilized in the facility or sold (Homagain *et al.*, 2015). The main outcomes of Bacenetti's study were that generating energy from biogas reduces fossil fuel use and greenhouse gas (GHG) emissions. Even in worst-case circumstances, it has been demonstrated that electricity generated from biogas sourced from biowaste is better than that

generated from fossil sources, at least in terms of reducing global warming (Bacchetti *et al.*, 2016).

Waste may provide cleaner electricity (Figure 2. 5), but if it is not properly managed, it may have many negative effects. It is not surprising that many researchers acknowledge that incineration has a better environmental impact than AD when disposing of waste. Although AD is a considerably more suitable technique for waste disposal or energy recovery from landfilling, developing nations may not be able to afford this technology (Salvador *et al.*, 2019).



**Figure 2. 5 Using Anaerobic Digestion to produce electricity.**

(Source: Sanscartier, MacLean and Saville, (2012) )

## 2.5 Life Cycle Assessment

Life Cycle Assessment (LCA) is an internationally recognized standardized methodology (ISO, 2006). LCA encompasses the entire lifespan of a product, spanning from the estimation of raw materials and production to consumption, end-of-life management, treatment, recycling, and disposal. It focuses on evaluating the environmental aspects and potential impacts associated with a product's life cycle, including factors such as resource consumption, as well as the environmental consequences resulting from post-consumption activities (ISO, 2006).

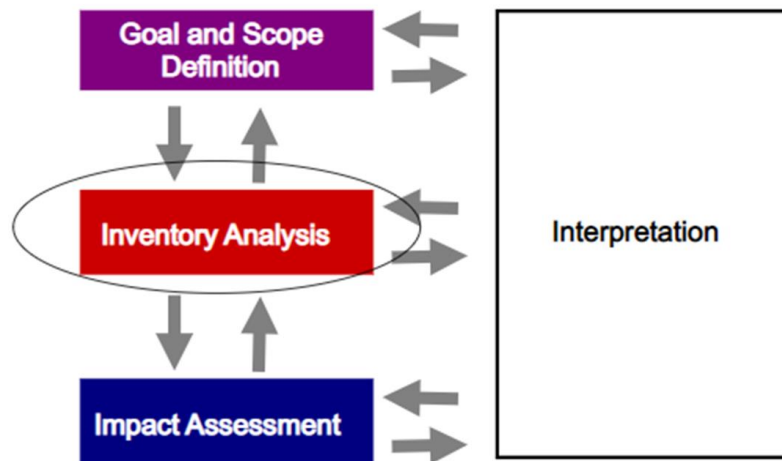
LCA evaluates the environmental impacts of a product or activity by identifying the materials and energy used, as well as waste and emissions released into the environment (Arena, Mastellone and Perugini, 2003). As stated by Allesch and Brunner, (2014), this methodology has been used extensively to assess waste management systems. The comparison of waste management techniques using life cycle approaches is becoming prevalent. LCA is simply meant to be a guide; therefore, to recommend the “optimal” system, various factors must be considered (Allesch and Brunner, 2014). In brief, LCA holistically examines the impact of a product or system on the environment. The fundamental limitation in conducting an LCA is the assumptions made, which results in inconsistent outcomes (Guinée *et al.*, 2011).

### **2.5.1 LCA methodology**

The LCA is a systematic, phased approach and consists of four components: goal and scope definition, inventory analysis, impact assessment, and interpretation as shown in Figure 2. 6 (Pieragostini, Mussati and Aguirre, 2012; Ayodele, Ogunjuyigbe and Alao, 2017). The four components are elaborated below:

- **Goal and Scope definition:** This defines the problem, objectives, and scope of the study. It includes the function of the product or system, the functional unit of the product, and the system boundaries.
- **Inventory Analysis:** This stage involves the quantification of emissions to air, as well as release of substances into water or on soil. The material, energy, and water usage are identified.
- **Impact Assessment:** The potential effects of the materials, energy, and water (inventory data) on the environment are studied. Some impact potentials considered are global warming potential, acidification potential, eutrophication potential, and human toxicity potential.

- Interpretation: The results from the impact assessment and the inventory analysis are evaluated to select the preferred product or process based on a clear understanding of the uncertainties and assumptions used (ISO, 2006).



**Figure 2. 6 The Phases of Life Cycle Assessment.**

(Source: Guinée et al., (2011))

### 2.5.2 Applications of LCA in similar studies

The utilization of biogas derived from municipal solid waste for electricity generation has garnered significant attention from researchers worldwide. Studies related to the LCA of bioenergy have focused on the efficiency of the system, which includes energy utilization, energy production, environmental impacts, and GHG emissions (Cherubini *et al.*, 2009; Gopal *et al.*, 2020; Jeswani, Chilvers and Azapagic, 2020). A study has shown that AD reduced GHG emissions by approximately three times relative to the base-case scenario (landfilling and composting), which was due to the carbon storage in compost and electricity generation from biogas (Nordahl, 2018). The main sources of emissions were biogas leakages from the facility, open storage of feedstock, and application of untreated digestate in the field (Vasco-Correa *et al.*, 2018).

Fusi *et al.*, (2016) conducted a life cycle environmental impact assessment focusing on biogas through anaerobic digestion in Northern Italy. Their findings revealed that electricity from biogas exhibited greater environmental sustainability than grid electricity across 11 impact categories. Biogas electricity displayed higher impacts than most renewables, with solar photovoltaics being a notable exception that has lower impacts.

Balcioglu, Jeswani and Azapagic, (2022), evaluated the environmental and economic sustainability of different feedstocks for anaerobic digestion in biogas plants in Turkey. The study showed that feedstocks with high solid contents and biogas yields, such as organic waste and chicken manure, yielded lower environmental impacts than current energy systems. This outcome was observed across 15 of 17 impact categories, including climate change.

A life cycle assessment conducted by Evangelisti *et al.*, (2014) examined energy generation from waste in the UK. The study highlighted that anaerobic digestion emerged as the most favourable treatment option when considering CO<sub>2</sub> and SO<sub>2</sub> savings, particularly when substituting non-renewable electricity, heat, and organic fertilizer. Incineration was identified as the second-best option in terms of environmental impact.

Ayodele, Ogunjuyigbe and Alao, (2017) investigated waste-to-energy technologies as a means of generating electricity using MSW in Nigeria. Their research indicated that a hybrid system combining incineration and anaerobic digestion displayed considerable potential, particularly in terms of global warming potential and ecosystem impact. The hybrid INC/AD approach exhibited the potential to reduce greenhouse gas emissions by 75.7%–93.3% compared to landfilling without energy recovery. Hence, the combination of INC/AD is the most suitable waste management strategy for Nigeria, considering its potential to produce energy.

In Ghana, there is a lack of widespread attention to the life cycle assessment (LCA) of electricity generation from MSW. Researchers have begun to explore the energy potential of biogas derived from municipal solid waste. Cudjoe and Mensah, (2021) assessed the electricity

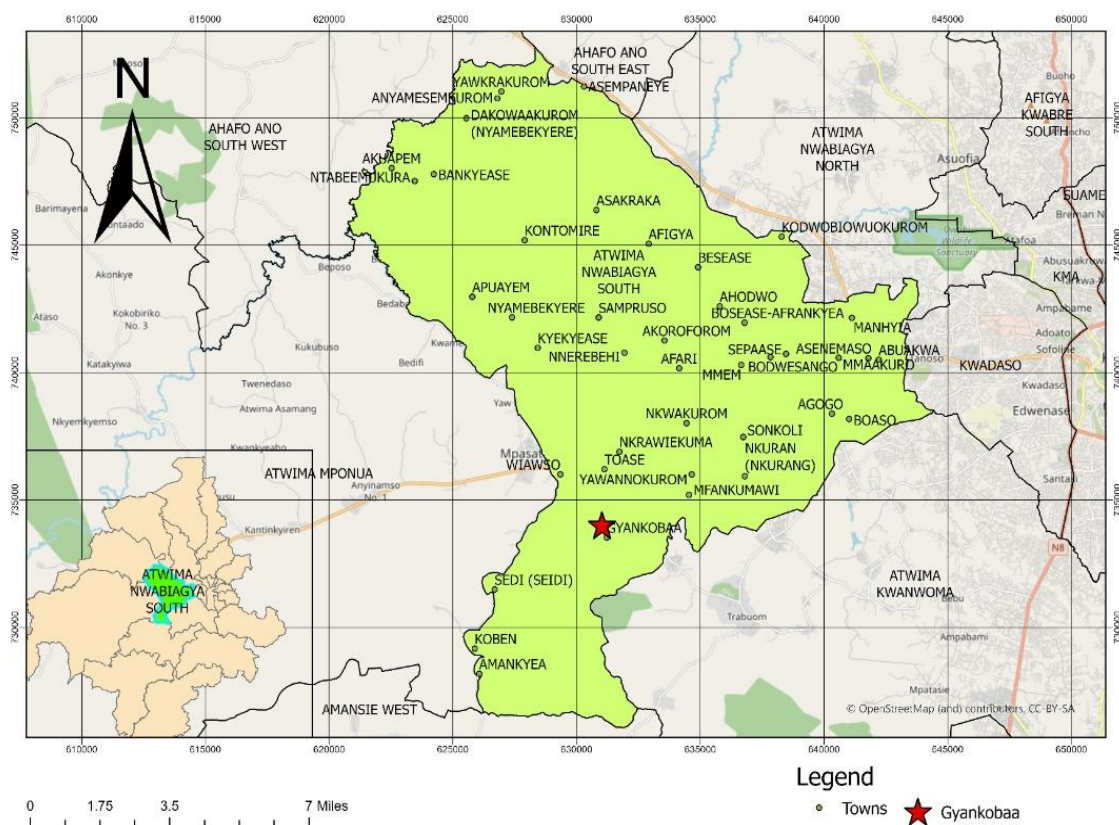
generation potential of biogas from food waste using anaerobic digestion technologies. Their study estimated waste generation in Accra and Kumasi between 2020-2039, projecting amounts ranging from 899,000 to 3,359,000 tons per year and 915,000 to 3,159,000 tons per year, respectively. The corresponding power generation estimates were between 80.43 and 300.49 GWh per year for Accra and 60.63 and 209.31 GWh per year for Kumasi.

## CHAPTER THREE

### MATERIALS AND METHODS

#### 3.1 Experimental site selection

The environmental impact of electricity generation from the anaerobic digestion of MSW was assessed in this study using a hybrid waste-to-energy plant at Gyankobaa in the Atwima Nwabiagya Municipality ( $6^{\circ} 32' 6.75''$  N,  $1^{\circ} 36' 2.00''$  W), Ghana, as shown in Figure 3. 1. The hybrid waste-to-energy plant consists of a solar PV and a biogas plant. The focus of this study however was on the biogas plant (AD).



**Figure 3. 1 Study site location in the Atwima Nwabiagya (South) Municipal Assembly, Ghana.**

### 3.2 Description of the Anaerobic Digestion Plant

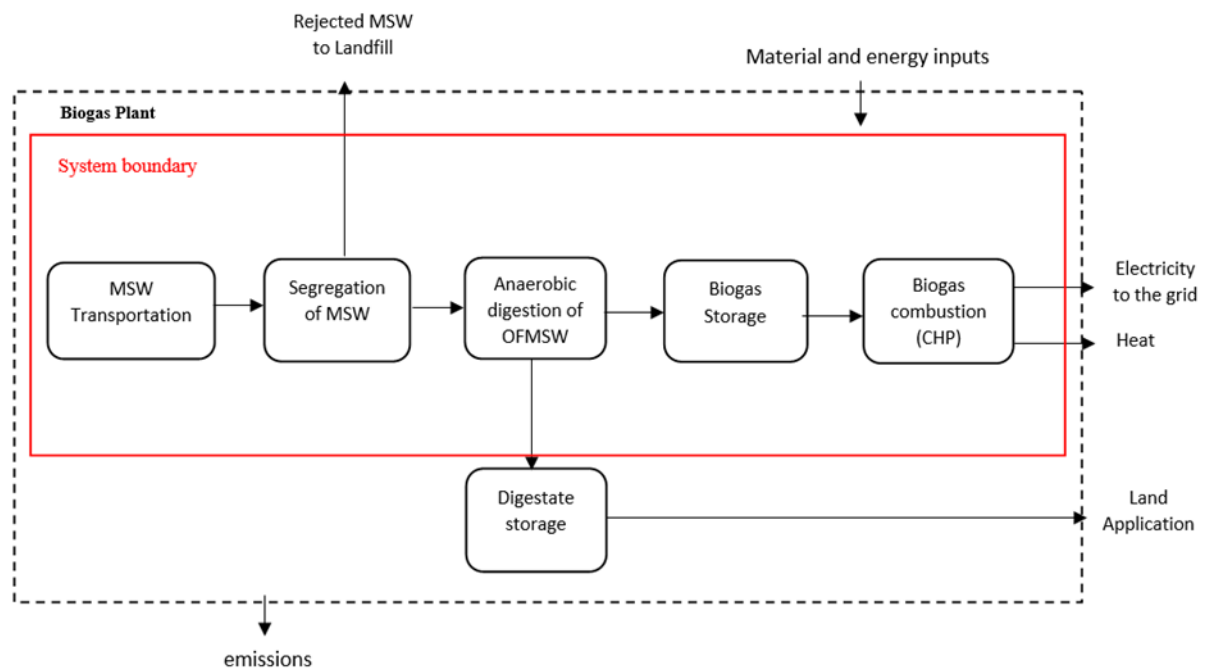
The Anaerobic Digestion plant was designed to process about 8,615 tons of municipal solid waste per year for the generation of 805,574 kWh of electricity. The waste received at the facility is not source-separated so there is a sorting facility on the site to pre-process the waste. The sorting facility consists of a trommel screen, magnetic separator, and shredder as the main units. The AD plant consists of a 1000 m<sup>3</sup> CSTR closed-dome anaerobic digester (Figure 3. 2), a digestate storage tank, and a 100-kW Combined heat and power plant (CHP).



**Figure 3. 2 Main component of the Anaerobic digestion plant.**

The MSW collected from Atwima Nwabiagya Municipality is unloaded into the waste storage tanks. The waste is transported to the segregation unit for preprocessing. In the unit, the first step is to manually pre-sort large waste items from the MSW. This is followed by the separation of the organic and inorganic waste using a Trommel screen. The ferrous metals are removed using a magnetic separator. Approximately 96% of the organic waste is retained after preprocessing. The organic waste is milled to fine particle size, after which water is added to the mixer to reduce the total solids content. OFMSW is temporarily stored in a grid carnal before it is fed to the CSTR digester. Finally, anaerobic digestion is performed with a retention

time of 21 days. The biogas produced is stored, pre-conditioned with iron stabilizers, and dehydrated before being directed to the 100-kW CHP to produce electricity and thermal energy. The electricity produced is used internally though it was initially planned to be fed to the grid while the heat is used for heating the digesters and the excess is dissipated by fan-coolers. To reduce the carbon footprint of the process, a 2000 m<sup>2</sup> roof-mounted solar PV system was used to provide energy for the operation of the facility. Two water tanks were used to store rainwater for use in the process.



**Figure 3. 3 Flow diagram of the anaerobic digestion plant (system boundary)**

### 3.3 Goal and scope definition

Defining the goal and scope is a crucial step in the LCA process. The study defined the primary functions of the AD facility as waste management and electricity production. It chose a functional unit of “generation of 805,574 kWh of Electricity per year” for the study. The system boundary as shown in Figure 3. 3 includes the transportation of MSW to the facility, the segregation of MSW, the anaerobic digestion of OFMSW, and energy generation from the

biogas. Generation and collection of waste, the digestate storage and its application on the field, the distribution of electricity, and the construction of the facility were excluded in the analysis (Bruno *et al.*, 2023). The impact of building the AD plant and CHP unit is excluded in the study because it has relatively low emissions compared to the usage phase (Sandanayake, Zhang and Setunge, 2018).

### **3.3.1 Life Cycle Inventory**

The main activity in the LCA's life cycle inventory phase is data collection. The data for the foreground system were obtained from the plant owners, academic publications, and technical documents. The EcoInvent Database version 3.8 provided the background data (Ciroth, Barreiros and Jürgens, 2021).

### **3.3.2 Transportation of Waste**

Waste collection and transportation in Atwima Nwabiagya were carried out by diesel-refused skip trucks (23 tons), which collect the MSW from households and commercial areas and deliver it to the waste treatment site. Data on the transportation of the MSW was obtained from Zoomlion Ghana Limited, the largest private waste management company in Ghana, through questionnaire and direct interviews. This included the quantity of waste transported, distance covered, and fuel consumed by vehicles. An estimated average distance of 10 km was chosen for the distance from the waste sources to the waste treatment plant as neighboring Municipalities that contribute to feedstock supply within a 10 km radius.

### **3.3.3 Segregation of Municipal Solid Waste**

The waste treatment facility has a sorting unit that segregates the mixed waste into organic waste and non-degradable fractions. The study performed material and energy balances on the sorting unit based on data from the plant owner. The calculation determined the input and output parameters.

**Table 3. 1 Power consumption data of equipment in Waste Segregation unit**

<b>Equipment</b>	<b>Capacity (kW)</b>
Feed Conveyor	3.375
Product Conveyor (2)	3
Axial Blower	1.125
Blower	7.5
Trommel feed Conveyor	2.25
Reject Conveyor	1.5
Trommel Screen	3.75
Hydraulic Baling Machine	3.75
Manual Segregation Conveyor	2.25
MSW Twin Shaft Shredder (2)	18.75
Star Delta Grinder Fwd	18.75
<b>Total</b>	<b>66</b>

Parameters:

Operating time = 20 hours/day

Days in the year = 365 days

Total electricity consumption per year = 481,800 kWh/year

### 3.3.3.1 Anaerobic Digestion of Organic Fraction of Municipal Solid Waste

The AD plant comprises a 1000 m<sup>3</sup> CSTR closed-dome anaerobic digester, a digestate storage tank, and a 100-kW combined heat and power plant. The reactor receives an organic fraction of the municipal solid waste and mixes it with fresh water. The digester operates at a mesophilic temperature of 38°C, which the study assumed as the temperature for modelling. The study determined the thermal requirement of the anaerobic digester using energy balance across the unit.

Electricity consumption for this plant was calculated similarly to the segregated unit above.

**Table 3. 2 Biogas plant equipment data**

<b>Equipment</b>	<b>Capacity (kW)</b>
Jialong Conveyor	3
Mechanical grill	0.75
Paddle agitator	5.5
Hydraulic circulation pipeline pump	3
Tank side mixer device	7.5
Submersible cutting feed pump	5.5
Submersible biogas slurry feed pump	2.2
Submersible cutting pump	0.75
Hot water circulation pipeline pump	0.75
Roots booster fan	2.2
Biogas holder booster fan	0.75
Solid-liquid separator	4.0
<b>Total</b>	<b>35.9</b>

## Parameters

Operating hours = 24 hours/day

Duration = 365 days/year

Total electricity consumption per year = 314,484 kWh/year

### 3.3.3.2 Thermal heat requirement for Anaerobic Digester

Ghana has a hot climate with an average annual temperature range of 24-30 °C. However, the temperature can vary from 18 °C in the south to 40 °C in the north, depending on the location and season (Asante and Amuakwa-Mensah, 2015; Nunfam *et al.*, 2021). The energy demand of the AD unit was estimated by assuming a temperature of 27.5 °C for both the influent and the ambient air. The specific heat capacity of the input was assumed to be 4.2 kJ/kg °C, similar to that of water. The heat transfer coefficient for the anaerobic digester was taken as 2.5 kJ/m<sup>2</sup>.h.K (Andreoli, Sperling and Fernandes, 2007; Dhar, Nakhla and Ray, 2012; Li *et al.*, 2017).

#### *Parameters*

Volume of biodigester = 1000 m<sup>3</sup>

Mass of feedstock = 3,800 tons/ year

Specific heat capacity of water used = 4.2 kJ/kg °C

Heat transfer coefficient = 2.5 kJ/m<sup>2</sup>.h.K

Heat loss =  $U \times A \times (T_1 - T_2)$

Where:

U = Overall heat transfer coefficient (W/m<sup>2</sup>K) = 2.5 kJ/m<sup>2</sup>.h.K

A = Surface area of the digester (m<sup>2</sup>) = 502 m<sup>2</sup>

T<sub>1</sub> = Temperature of the digester (°C) = 38 °C

T<sub>2</sub> = Temperature of ambient air (°C) = 27.5 °C

The digester was designed with a cylindrical shape and an average height-to-diameter ratio of 2:1 ( $h=2D$ ), following (Moran, 2018). The volume of the digester was chosen to match the typical range of 700 to 1200 m<sup>3</sup> for industrial AD plants, as reported by (Bolzonella *et al.*, 2005). The height and diameter of the tank were calculated based on the height-to-diameter ratio.

$$V_{digester} = \frac{\pi D^2}{4} \times h = \frac{\pi D^3}{2} = 1000m^3$$

$$D = 8m$$

$$h = 20m$$

$$A = \pi Dh = \pi \times 8 \times 20 = 502 m^2$$

$$Q_{loss} = U \times A \times (T_{digester} - T_{ambient})$$

$$Q_{loss} = 2.5 \times 365 \times 24 \times 502 \times (38 - 27.5)$$

$$Q_{loss} = 115,434,900 \frac{kJ}{y} = 32065 \frac{kWh}{y}$$

$$\text{Heat requirement} = m \times C_p \times (T_3 - T_4)$$

Where:

$$m = \text{Mass of the feedstock being digested (kg)} = 3,800 \text{ tons}$$

$$C_p = \text{Specific heat capacity of the feedstock (kJ/kg K)} = 4.18 \text{ kJ/kg C}$$

$$T_3 = \text{Temperature required for digestion (}^\circ\text{C)} = 38^\circ\text{C}$$

$$T_4 = \text{Temperature of the feedstock (}^\circ\text{C)} = 27.5^\circ\text{C}$$

$$Q \text{ required} = 3,800,000 \times 4.2 \times (38-27.5) = 46,550 \text{ kWh/ year}$$

$$\text{The thermal energy required} = \text{heat requirement} + \text{heat loss}$$

$$\text{The thermal energy required} = 78,615 \text{ kWh/year}$$

### 3.3.4 Emissions estimations

The study performed emission estimations on the anaerobic digester and the combined heat and power plant units. The emissions included greenhouse gases such as methane (CH<sub>4</sub>), nitrous oxides (NO<sub>x</sub>), and dinitrogen monoxide (N<sub>2</sub>O), as commonly reported in literature (Ayodele, Ogunjuyigbe and Alao, 2017). The study assumed 60% methane content in the biogas and 2.5% methane loss for the AD following Scheutz and Fredenslund, (2019). The emission factors for Danish decentralized CHP plants by Nielsen, Nielsen and Thomsen, (2010) are used to estimate the emissions from the CHP plant. According to these factors, combustion of 1 GJ of biogas produces 1.6 g of N<sub>2</sub>O and 202 g of NO<sub>x</sub>.

#### 3.3.4.1 Methane emission calculation from Anaerobic Digestion

##### *Parameters*

Methane content = 60%

Biogas produced = 352, 589 Nm<sup>3</sup>/year

Density = 0.716 kg/m<sup>3</sup> (UNFCCC, 2003)

Biogas percent leakage = 2.5 % (average value of European Biogas plants).

##### *Calculation*

Methane produced = 352, 589 Nm<sup>3</sup> x 0.6

Biomethane = 211,553.4 Nm<sup>3</sup>

Mass of Methane = 211,553.4 Nm<sup>3</sup> x 0.716 kg/m<sup>3</sup>

= 151,472.23 kg

Methane leaked (2.5% loss) = 3,786.8 kg

### 3.3.4.2 CHP emission estimations

Parameters used:

Energy value of Biomethane = 37.78 MJ/m<sup>3</sup>

Volume of Biomethane = 211,553.4 Nm<sup>3</sup>

Total energy = 7,992,487.45 MJ = 7992.49 GJ

Using the fuel conversion efficiency, we can estimate the emissions of pollutants as follows:

- NO<sub>x</sub>: 202 g/GJ × 7992.49 GJ = 1614.48 kg/year

- N<sub>2</sub>O: 1.6 g/GJ × 7992.49 GJ = 12.79 kg/year

### 3.4 Life Cycle Impact Assessment

The study evaluated the environmental impacts of the system by analyzing the results from the inventory analysis, specifically the inventory table, within the context of the goals and scope of the study. It performed the LCIA following the guidelines of ISO 14040/14044 and using OpenLCA 1.11.0 as the LCA assessment tool to set up the model for the anaerobic digestion process. The LCIA involved three steps: 1) selecting and classifying impact categories, 2) characterization, and 3) normalization. The study used the CML-IA baseline characterization method (CML - Department of Industrial Ecology, 2016) of the Institute of Environmental Sciences (CML) and World (2010) normalization method for the LCIA because it is commonly used in several studies (Grosso *et al.*, 2012; Biancini *et al.*, 2020). The impact method consists mainly of impact categories such as abiotic depletion potential (kg Sb eq), abiotic depletion potential (fossil fuels) (MJ), acidification potential (kg SO<sub>2</sub> eq), eutrophication potential (kg PO<sub>4</sub><sup>3-</sup> eq), global warming potential 100a (kg CO<sub>2</sub> eq), human toxicity potential (kg 1,4-DCB eq), marine ecotoxicity potential (kg 1,4-DCB eq), ozone depletion potential (kg CFC-11 eq), photochemical oxidant creation potential (kg C<sub>2</sub>H<sub>4</sub> eq), and terrestrial ecotoxicity potential (kg 1,4-DCB eq).

### **3.5 Scenario Analysis**

Scenario analysis per ISO 14040/44 (2006a, 2006b), is a common form of sensitivity analysis. This involves the assessment of potential variations in LCA results resulting from discrete choices (Hauschild, M. Z. Rosenbaum and Olsen, 2018; Igos et al., 2019). It is employed to assess the uncertainty arising from various choices such as functional units, allocation procedures, assumptions in life cycle inventory, life cycle impact assessment methodologies, temporal variability, and spatial variability.

Three scenarios are considered in this analysis:

1. The first, which was the baseline, was modelled using an open-ground solar PV plant as the electricity source for the anaerobic digestion system.
2. The second scenario labelled as ‘scenario 1’ was modelled using an electricity production mix for Ghana in 2018 as provided by the EcoInvent Database in OpenLCA with the following consumption composition: Solar PV (0.2%), Natural Gas (34.4%), Oil (25%) and Hydro (40.4%) as a substitute for the Solar PV in the baseline scenario.
3. The third scenario labelled ‘Scenario 2’ was modelled using electricity produced from the biogas engine (combined heat and power plant) as substitute for the Solar PV in the baseline scenario.

### **3.6 Uncertainty Analysis**

The level of uncertainty in the results is contingent on the uncertainty in the model parameters used. To quantify the uncertainty in the scenarios and the sensitivity analysis, error propagation was employed through Monte Carlo simulations using OpenLCA 1.11.0. Monte Carlo simulation is the prevalent sampling technique in LCA and is supported by major LCA software platforms. (Groen, et al. 2014, Hauschild, Rosenbaum and Olsen 2018, Igos, et al. 2019). The fundamental principle of this sampling technique involves iteratively performing

model calculations by sampling the values from predetermined probability distributions for each input parameter. Consequently, the model output can be represented as a probability distribution (Hauschild, M. Z. Rosenbaum and Olsen, 2018; Igos *et al.*, 2019).

Standard deviations were assigned to individual parameters in the process inventories by utilizing data quality indicators within the pedigree matrices. The incorporation of pedigree matrices allows for the assessment of data reliability and completeness as well as geographical, technological, and temporal correlations (Ciroth *et al.*, 2016). For each scenario, the characteristic results were computed through 1000 iterations with dependent sampling (Henriksson, et al. 2014).

## CHAPTER FOUR

### RESULTS AND DISCUSSION

#### 4.1 Life Cycle Inventory

The inventory results in Figure 4. 1 highlight a clear distinction between the main input and output flows of the anaerobic digestion system. In terms of inputs, the system relies on various resources. This requires the transportation and segregation of 8,615,000 kg of MSW, indicating the significant role of waste collection and sorting. Additionally, the anaerobic digestion stage depends on 3,800,000 kg of biowaste and 1,400,000 kg of freshwater, emphasizing the importance of these materials in facilitating the digestion process. Furthermore, the system benefits from 48,180 kWh/year of electricity input from a solar PV plant, which contributes to power operations.

In contrast, the anaerobic digestion system produced notable outputs. It successfully converted biowaste into valuable energy resources, yielding a substantial net biogas production of 352,589 Nm<sup>3</sup>/year. The system's efficiency in harnessing energy is further demonstrated by the combined heat and power (CHP) stage, generating 805,574 kWh/year of electricity, and achieving a net thermal energy generation of 868,621 kWh/year.

The results of the quantification and compilation of the inventory for the input and output products of the anaerobic digestion process showed that the system holds great potential as an environmentally sustainable energy solution. The inventory compilation showed how an anaerobic digestion system takes inputs, such as municipal solid waste, biowaste, fresh water, and electricity, and through the process of anaerobic digestion and produced outputs, including electricity (from solar PV and CHP), biogas, and thermal energy.

**Table 4. 1 Inventory Data for Anaerobic Digestion of MSW**

<b>Process Stage</b>	<b>Unit</b>	<b>Value</b>	<b>Data Source</b>
<b>Transportation</b>	kg-km	86,150,000	Own calculation based on Waste Management Company data.
<b>Segregation of MSW</b>			
Municipal solid waste	kg/year	8,615,000	Plant Owner
Electricity from solar PV	kWh/year	481,800	Own calculations based on the Plant owner's data
<b>Anaerobic Digestion</b>			
Biowaste	kg/year	3,800,000	Plant Owner
Freshwater	kg/year	1,400,000	Plant Owner
Electricity from solar PV	kWh/year	314,484.0	Own calculation based on Plant Owner's data
Net biogas production	Nm <sup>3</sup> /year	352, 589	Plant Owner
<b>Emissions associated with AD</b>			

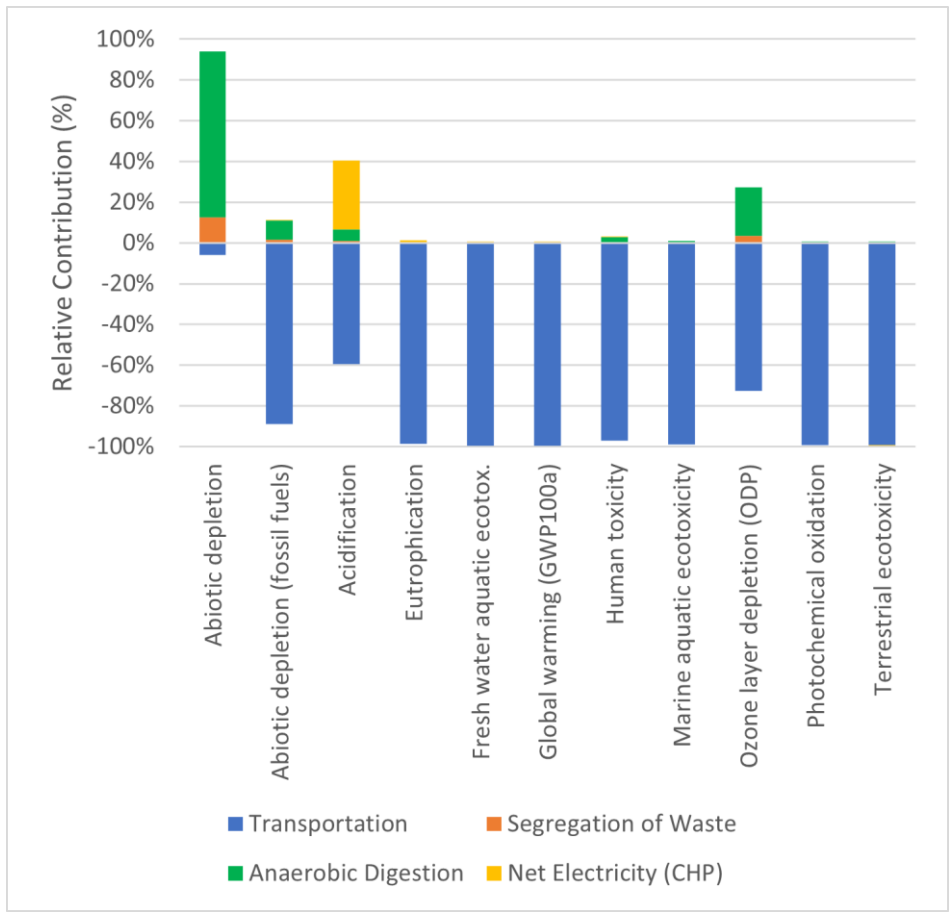
Methane loss	kg/year	3,786.8	Own calculations based on the plant Owner's data
<b>CHP</b>			
Electricity generated	kWh/year	805,574	Plant Owner
Net Thermal energy generated	kWh/year	868,621	Own calculation based on Plant Owner's data
<b>Emissions associated with CHP</b>			
N <sub>2</sub> O from CHP	kg/year	12.79	Own calculation based on Nielsen & Nielsen, 2011
NO <sub>x</sub> from CHP	kg/year	1614.48	Own calculation based on Nielsen & Nielsen, 2011

This study's demonstration of an anaerobic digestion system to convert waste into valuable energy resources is supported by empirical evidence. For instance, Cudjoe and Mensah, (2021) assessed the electricity generation potential of biogas from food waste using anaerobic digestion technologies. They found that with an estimated waste generation ranging from 899,000 to 3,359,000 tons per year in Accra, and from 915,000 to 3,159,000 tons per year in Kumasi, there was a potential for anaerobic digestion system to generate power between 80.43 and 300.49 GWh per year for Accra and between 60.63 and 209.31 GWh per year for Kumasi.

Again, the findings prove that the anaerobic digestion system is indeed a sustainable solution for waste management, as it can convert 8,615,000 kg of municipal solid waste and 3,800,000 kg (44%) of biowaste into renewable energy. This aligns with findings and assertions made by Amo-asamoah, Asumadu and Edwards, (2020); Seruga, (2021) that an anaerobic digestion system should be central to the waste management system of municipalities.

## **4.2 Impact Assessment**

Life cycle inventory data were used to model and compute the environmental impacts of the anaerobic digestion system using the CML-IA baseline method, which included characterization and normalization steps. During the characterization phase, the relative contribution of each impact category was adjusted to a scale of 100%. The contribution analysis as shown in Figure 4. 1 revealed that the transportation stage was the highest contributor to most of the impact categories, followed by the anaerobic digestion stage.



**Figure 4. 1 Environmental Profile for the Anaerobic Digestion System – Characterization**

**Table 4. 2 Contribution of different life cycle stages to the characterized impacts of the biogas plant (baseline).**

<b>Impact Category</b>	<b>Total</b>	<b>Transportation</b>	<b>Segregation</b>	<b>Anaerobic Digestion</b>	<b>Electricity Generation</b>
Abiotic depletion	3.39E+00	-1.01E-01	2.11E+00	1.38E+00	0.00E+00
Abiotic depletion (fossil fuels)	-1.86E+06	-2.56E+06	4.20E+05	2.74E+05	4.90E+00
Acidification	-2.71E+02	-1.42E+03	2.06E+02	1.35E+02	8.07E+02
Eutrophication	-2.17E+04	-2.21E+04	7.99E+01	5.21E+01	2.13E+02
Freshwater aquatic ecotoxicity.	-1.66E+07	-1.67E+07	6.12E+04	3.99E+04	6.72E+01
Global warming (GWP100a)	-5.34E+06	-5.41E+06	3.69E+04	2.41E+04	3.39E+03
Human toxicity	-1.55E+06	-1.65E+06	6.45E+04	4.21E+04	1.94E+03
Marine aquatic ecotoxicity	-8.01E+09	-8.18E+09	1.04E+08	6.78E+07	2.10E+03
Ozone layer depletion (ODP)	-1.49E-03	-8.63E-03	4.30E-03	2.82E-03	0.00E+00
Photochemical oxidation	-1.16E+03	-1.17E+03	1.10E+01	7.20E+00	0.00E+00
Terrestrial ecotoxicity	-1.21E+04	-1.22E+04	1.04E+02	6.81E+01	-4.67E-02

(Note: Positive values = more emissions than avoided = burden, Negative values = less emissions than avoided = benefit)

The impact assessment results as shown in Figure 4. 2 indicate that the anaerobic digestion system has both environmental benefits and burdens on different impact categories. The system has a positive impact on global warming, acidification, eutrophication, ozone depletion, photochemical oxidation, and various types of ecotoxicity and human toxicity. These benefits are mainly attributed to the avoidance of emissions from conventional waste disposal methods and electricity generation from fossil fuels, which are the main sources of greenhouse gases and air pollutants in Ghana (Amo-asamoah, Asumadu and Edwards, 2020). However, the system has a negative impact on abiotic depletion due to its resource consumption, especially for the transportation stage, which requires a high amount of fuel. Therefore, the system has a trade-off between reducing emissions and consuming resources, which affects its environmental performance and sustainability.

To facilitate a direct comparison between the impact categories, a normalization process was performed to standardize all impact categories according to a reference value. Normalization provides a context for characterized results by relating them to the total environmental impacts of a certain region or population (Guinée et al., 2002). In this study, the normalization was based on the world average data for the year 2000 (Goedkoop et al., 2013).

According to the normalization results (Figure 4. 3), the aggregated value of the environmental impact amounted to  $-4.92 \times 10^{-5}$ . The transportation stage contributes the most ( $7.70 \times 10^{14}$ ), followed by  $-7.43 \times 10^{11}$  benefit from electricity generation,  $-8.88 \times 10^{13}$  benefit from the segregation, and  $-5.79 \times 10^{13}$  benefit from the anaerobic digestion stage. Therefore, the transportation stage was recognized as the primary contributor to the environmental impacts including  $4.90 \times 10^{-9}$  impacts from abiotic depletion (fossil fuels).

This finding corroborates the study by Poeschl, Ward and Owende, (2012), which identified the collection and transportation of municipal solid waste (MSW) and chemical fertilizer application as the major contributors to greenhouse gas emissions from anaerobic digestion systems, due to their high demand for fuel consumption. However, this study differs from Poeschl, Ward and Owende, (2012) in terms of the impact categories considered and the functional unit used. Poeschl, Ward and Owende, (2012) focused only on global warming potential and used ton of MSW as the functional unit, while this study considered multiple impact categories and used kWh of electricity as the functional unit.

**Table 4. 3 Normalized environmental impact of the anaerobic digestion system.**

<b>Impact Category</b>	<b>Total</b>	<b>Transportation</b>	<b>Segregation</b>	<b>Anaerobic Digestion</b>	<b>Electricity Generation</b>
Abiotic depletion	1.62E-08	-6.23E+06	1.30E+08	8.51E+07	0.00E+00
Abiotic depletion (fossil fuels)	-4.90E-09	5.22E+14	-8.57E+13	-5.59E+13	-1.00E+09
Acidification	-1.14E-09	1.25E+12	-1.81E+11	-1.19E+11	-7.10E+11
Eutrophication	-1.37E-07	1.61E+11	-5.82E+08	-3.80E+08	-1.55E+09
Freshwater aquatic ecotoxicity.	-7.04E-06	2.37E+12	-8.70E+09	-5.67E+09	-9.55E+06
Global warming (GWP100a)	-1.28E-07	4.24E+13	-2.89E+11	-1.89E+11	-2.65E+10

Human toxicity	- 6.00E- 07	2.75E+12	-1.08E+11	-7.02E+10	-3.23E+09
Marine aquatic ecotoxicity	- 4.13E- 05	1.98E+14	-2.52E+12	-1.64E+12	-5.08E+07
Ozone layer depletion (ODP)	- 6.59E- 12	-1.31E+09	-6.53E+08	-4.28E+08	0.00E+00
Photochemical oxidation	- 3.15E- 08	3.72E+10	-3.50E+08	-2.29E+08	0.00E+00
Terrestrial ecotoxicity	- 1.10E- 08	1.11E+12	-9.42E+09	-6.17E+09	4.23E+06

The results of this study also relate to the local or regional context of Ghana, where waste management is a major challenge and electricity supply is unreliable (Amo-asamoah, Asumadu and Edwards, 2020). Anaerobic digestion can provide a viable solution for managing organic waste and generating renewable energy in Ghanaian municipalities, as demonstrated by Amo-asamoah, Asumadu and Edwards, (2020), who evaluated the feasibility of using anaerobic digestion for managing organic waste in Ghanaian municipalities. They suggested that anaerobic digestion should be central to the waste management system of municipalities.

### **4.3 Interpretation**

The scenario and uncertainty analysis results of the model are presented by comparing different scenarios and using monte Carlo simulations.

#### **4.3.1 Scenario Analysis**

Two scenarios are considered in this analysis: scenario 1 uses the Ghana electricity grid in 2018 as the electricity source for the anaerobic digestion process, while scenario 2 uses electricity from biogas engine. The choice of these scenarios reflects the different options for electricity supply in Ghana, which vary in terms of availability, cost, and environmental impacts.

In Scenario 1, emission savings in abiotic depletion was significantly lower compared to the baseline, and slightly lower in the abiotic depletion (fossil fuels) category. However, the remaining impact categories had a significant increase in emissions compared to the baseline.

The scenario had the highest impact on the acidification impact category (725%).

In Scenario 2, where electricity from a biogas was used, the scenario did not have a significant impact on the human toxicity category, freshwater aquatic ecotoxicity, and marine aquatic ecotoxicity but was slightly lower in eutrophication, abiotic depletion (fossil fuels), global warming, photochemical oxidation, and terrestrial ecotoxicity as compared to the baseline. Emissions in the remaining impact categories were significantly lower than the baseline.

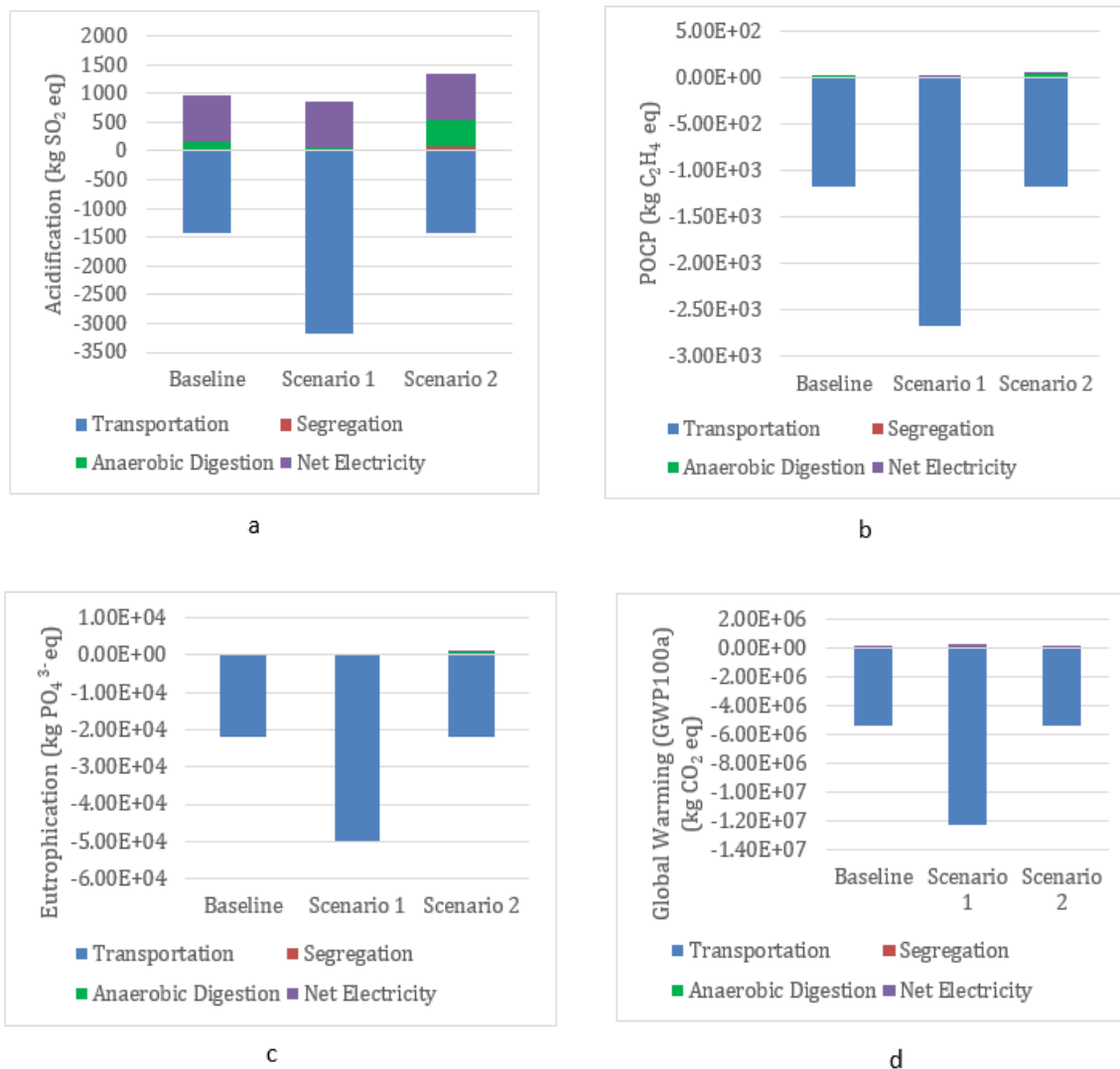
The lowest emission reduction was recorded in the ozone layer depletion category (2637%).

The main reason for this difference is that scenario 1 relies on an electricity production mix that has a high share of fossil fuel-based energy sources

**Table 4. 4 Comparison of environmental impacts for all scenarios per impact categories.**

<b>Impact Category</b>	<b>Base</b>	<b>Scenario 1</b>	<b>Sensitivity analysis of S1 (%)</b>	<b>Scenario 2</b>	<b>Sensitivity analysis of S2 (%)</b>
Abiotic depletion	3.39E+00	1.33E-02	-99.61%	1.36E+00	-59.74%
Abiotic depletion (fossil fuels)	-1.86E+06	-1.64E+06	-11.73%	-1.54E+06	-17.21%
Acidification	-2.71E+02	-2.24E+03	724.95%	5.79E+02	-313.69%
Eutrophication	-2.17E+04	-4.97E+04	129.20%	-2.02E+04	-6.71%
Freshwater aquatic ecotoxicity.	-1.66E+07	-3.79E+07	128.54%	-1.65E+07	-0.52%
Global warming (GWP100a)	-5.34E+06	-1.19E+07	123.15%	-5.15E+06	-3.56%
Human toxicity	-1.55E+06	-3.73E+06	140.93%	-1.56E+06	0.55%
Marine aquatic ecotoxicity	-8.01E+09	-1.85E+10	131.27%	-8.01E+09	-0.03%
Ozone layer depletion (ODP)	-1.49E-03	-7.04E-03	372.24%	3.78E-02	-2637%
Photochemical oxidation	-1.16E+03	-2.62E+03	125.94%	-1.07E+03	-7.63%
Terrestrial ecotoxicity	-1.21E+04	-2.77E+04	128.88%	-9.83E+03	-18.76%

that have higher emissions and resource consumption than biogas, which is a renewable and carbon-neutral energy source (Amo-asamoah, Asumadu and Edwards, 2020).



**Figure 4. 2 Sensitivity analysis results for all scenarios in the (a) acidification potential, (b) photochemical oxidant creation potential, (c) eutrophication potential, and (d) global warming potential categories**

The environmental impacts of the scenarios are assessed using four impact categories: abiotic depletion, marine aquatic ecotoxicity, acidification potential, and global warming potential.

According to results in Figure 4. 2 a, all scenarios show an equal and significant benefit with the Net Electricity contributing 807.24 kg SO<sub>2</sub> eq. to the acidification potential in the baseline

scenario. The primary cause of acidification is the emission of large quantities of sulphur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>) into the atmosphere. The electricity consumed represents the generation of electricity from renewable or low-impact sources, which have significantly lower emissions of acidifying substances than fossil fuel-based energy sources. Transportation consistently emerged as a hotspot in all the scenarios. This is because of the combustion of fossil fuels, which releases pollutants into the atmosphere. The Photochemical oxidant creation potential, eutrophication potential, and global warming potential all showed similar results from Figure 4. 2 b, c, and d respectively. Transportation of the waste contributed the most to the impact results followed by the anaerobic digestion stage in all scenarios. Emissions from the anaerobic digestion stage could be due to the leakage of biogas from pipelines and flaring of excess methane.

The results of this study are consistent with previous studies that found that the electricity source is a key factor affecting the environmental performance of anaerobic digestion systems (Tian et al., 2021; Barahmand and Samarakoon, 2022). The sensitivity results also suggest some trade-offs and synergies among the impact categories. For example, scenario 1 has a trade-off between abiotic depletion and global warming potential, while scenario 2 has a synergy between these two impact categories. The results also imply some improvement measures for reducing the hotspots of transportation and biogas leakage, which contribute to most of the impacts in all scenarios. Transportation is responsible for the emissions of pollutants from fossil fuel combustion, while biogas leakage is responsible for the emissions of methane from pipelines and flaring systems. These hotspots can be reduced by optimizing the transportation routes and distances, and by implementing regular maintenance and inspection of digester systems and flaring systems.

### **4.3.2 Uncertainty analysis results**

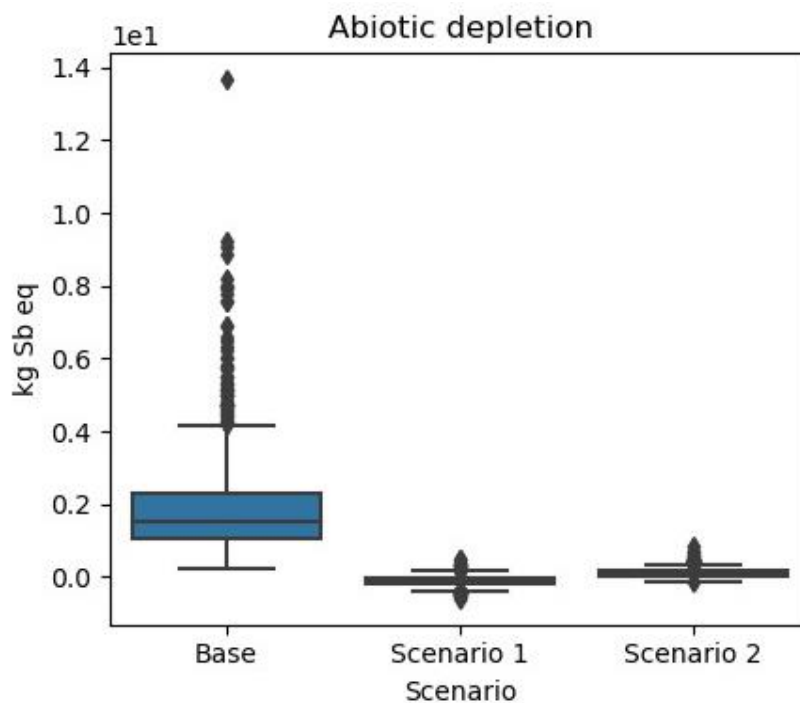
According to Igos *et al.*, (2019), uncertainty in life cycle assessment (LCA) can be categorized into three main aspects: quantity, model structure, and context.

Quantity uncertainty refers to the uncertainty in the number of inputs and parameters used in the LCA inventory. In this evaluation, data quality indicators are used to account for quantity uncertainty. The supplementary information provides the scores for each parameter. Among these indicators, data reliability and temporal correlation were the most significant contributors to quantity uncertainty. This is because background data often relied on qualified estimates from datasets dating back six years or more.

Model structure uncertainty arises when there is a discrepancy between the mathematical relationships used in the model and the actual causal structure of the system being assessed. On the contrary, context uncertainty relates to methodological choices made in defining the goal and scope of the study. This includes factors such as the definition of the functional unit, selection of marginal suppliers, and consideration of indirect consequential effects. Scenario analyses are conducted to address both model structure and context uncertainties in this assessment.

### Abiotic Depletion

The uncertainty results (Figure 4. 3) show that scenario 1 is the best option for reducing abiotic depletion, as it has a negative median impact and a significant difference from the baseline. Scenario 2 is the second-best option, as it has a lower median impact and a significant difference from the baseline, but not as strong as scenario 1. The baseline is the worst option, as it has a positive median impact and a high uncertainty and variability. However, there is a trade-off between potential and risk for each scenario, as scenario 1 has the lowest minimum impact and scenario 2 has the highest minimum impact.

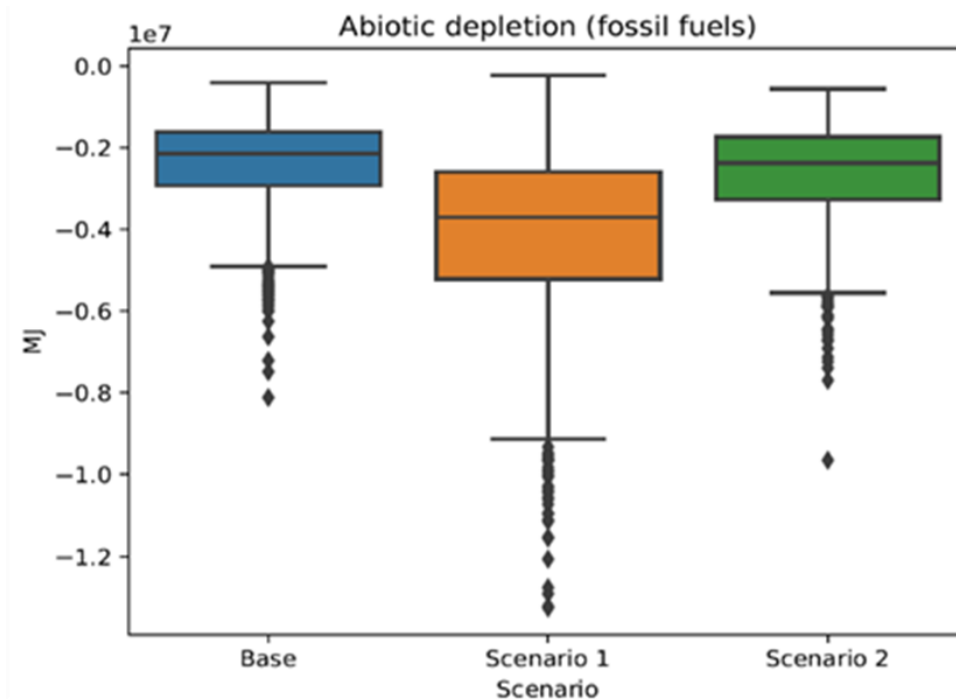


**Figure 4. 3 Uncertainty result in all scenarios for the abiotic depletion category**

### Abiotic Depletion (Fossil Fuels)

The uncertainty results Figure 4. 4 shows that scenario 1 is the best option for reducing abiotic depletion (fossil fuels), as it has the lowest median impact and a significant difference from the baseline and scenario 2. Scenario 2 is the second-best option, as it has a negative median impact and a significant difference from the baseline, but not as strong as scenario 1. The baseline is

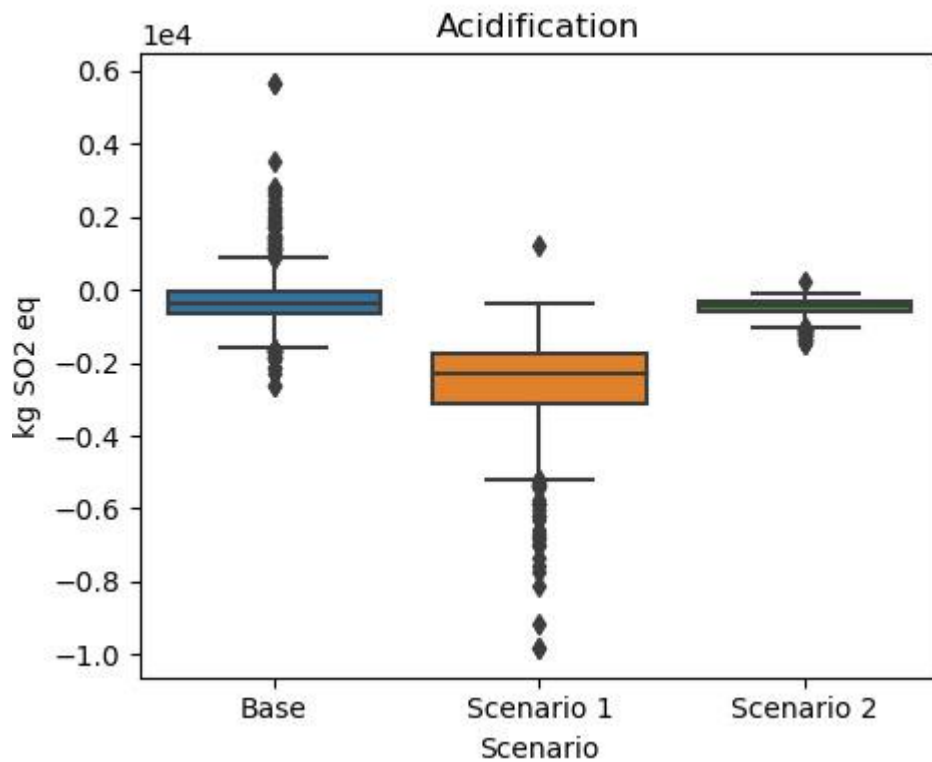
the worst option, as it has a positive median impact and a high uncertainty and variability. However, there is a trade-off between potential and risk for each scenario, as scenario 1 has the lowest minimum impact and scenario 2 has the highest minimum impact.



**Figure 4. 4 uncertainty result in all scenarios for the abiotic depletion (fossil fuels) category**

**Acidification**

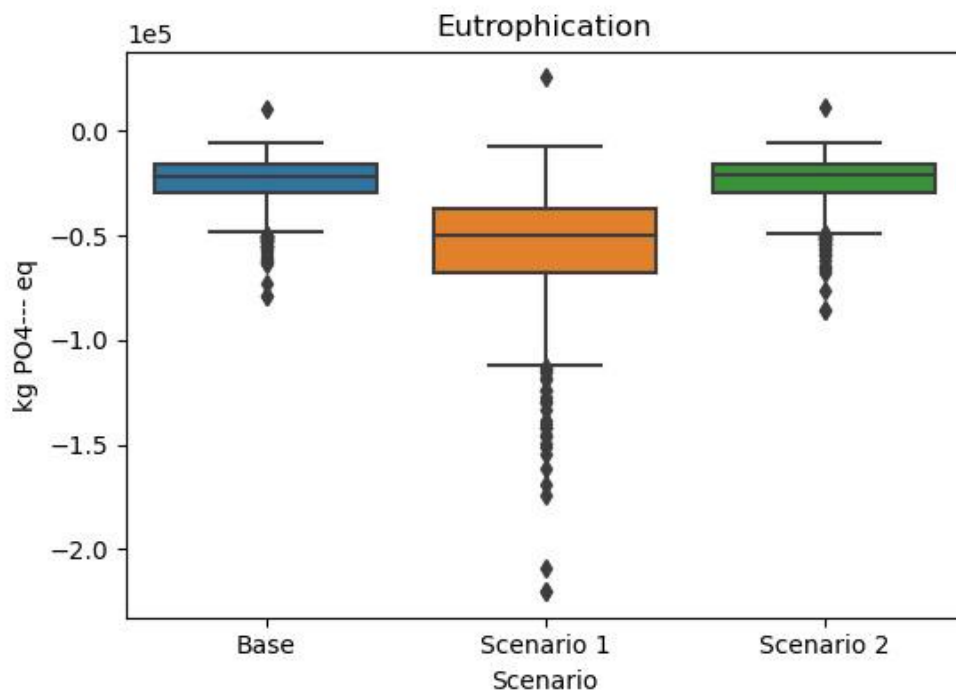
The uncertainty results Figure 4. 5 show that scenario 1 is the best option for reducing acidification, as it has the lowest median impact and a significant difference from the baseline and scenario 2. Scenario 2 is the second-best option, as it has a negative median impact and a significant difference from the baseline, but not as strong as scenario 1. The baseline is the worst option, as it has a positive median impact and a high uncertainty and variability. However, there is a trade-off between potential and risk for each scenario, as scenario 1 has the lowest minimum impact and scenario 2 has the highest minimum impact.



**Figure 4. 5 uncertainty result in all scenarios for the acidification category**

### **Eutrophication**

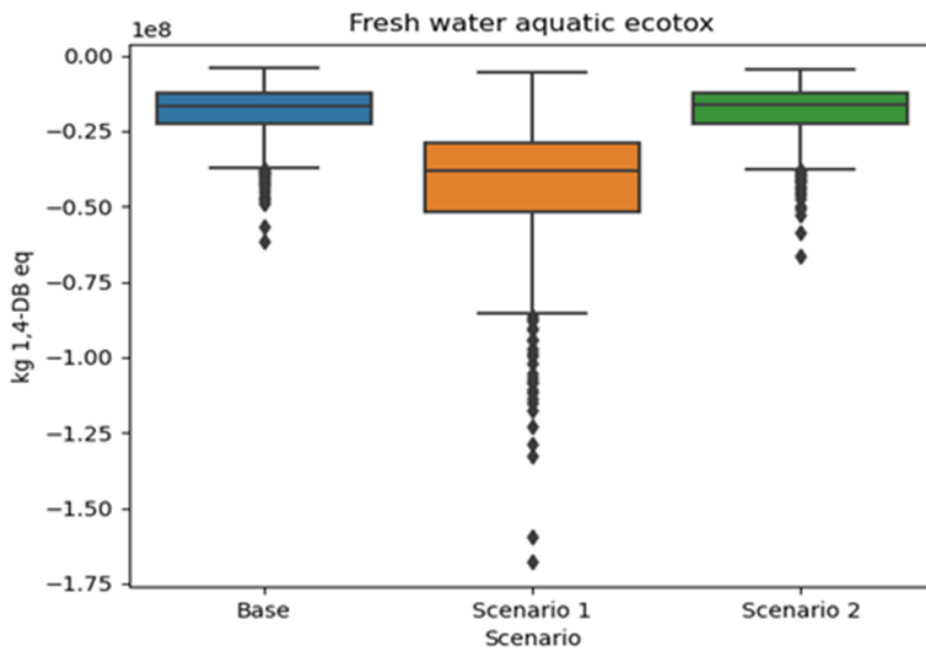
From Figure 4. 6, the Baseline scenario shows the highest median eutrophication potential, indicating a significant potential for eutrophication in this scenario. However, the results are highly uncertain with a large standard deviation, implying that there is substantial variability in the potential outcomes. Scenario 1 demonstrates a considerably lower median eutrophication potential compared to the Baseline scenario. The result is less uncertain, with a smaller standard deviation, suggesting a more predictable outcome regarding eutrophication potential. Scenario 2 has a positive median eutrophication potential, indicating a potential for reducing eutrophication compared to the Baseline scenario. The result is relatively stable and less uncertain, with a moderate standard deviation.



**Figure 4. 6 uncertainty result in all scenarios for the eutrophication category**

### **Freshwater aquatic ecotoxicity**

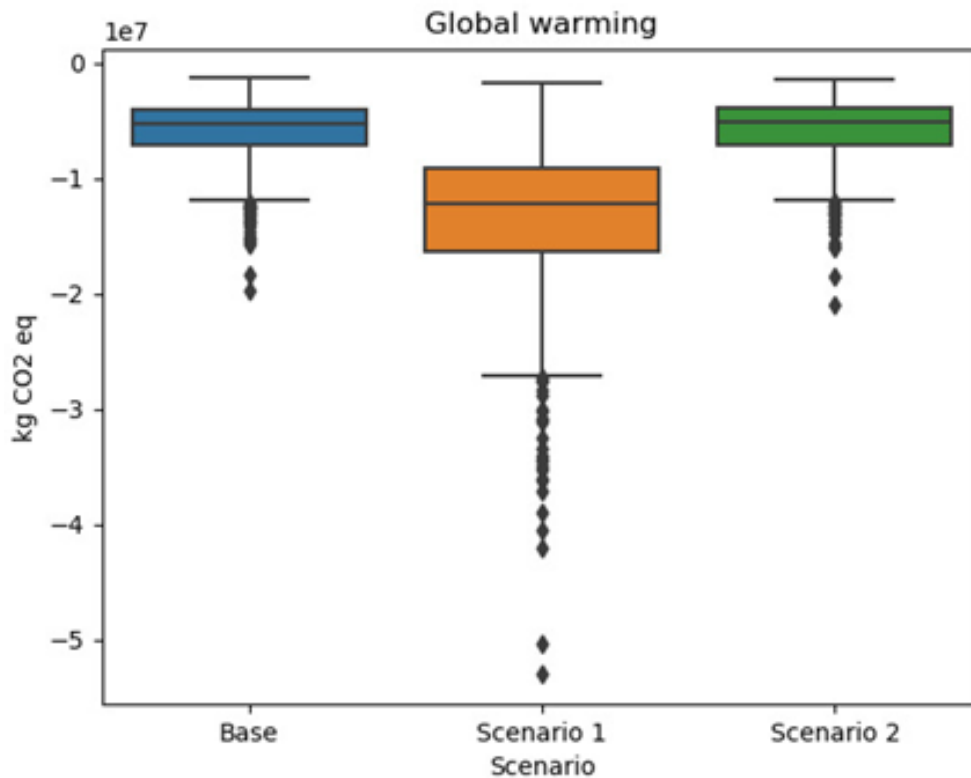
From Figure 4. 7, the Baseline scenario has a moderate median ecotoxicity potential but is associated with a significant amount of uncertainty and variability. Scenario 1 exhibits the most negative median ecotoxicity potential, suggesting a potentially higher risk of ecotoxicity. However, this scenario also has the largest uncertainty, indicating less confidence in the results. Scenario 2 has a less negative median ecotoxicity potential compared to Scenario 1 and a moderate standard deviation, implying a more stable and predictable outcome compared to Scenario 1.



**Figure 4. 7 Uncertainty result in all scenarios for the freshwater aquatic ecotoxicity category**

**Global warming potential**

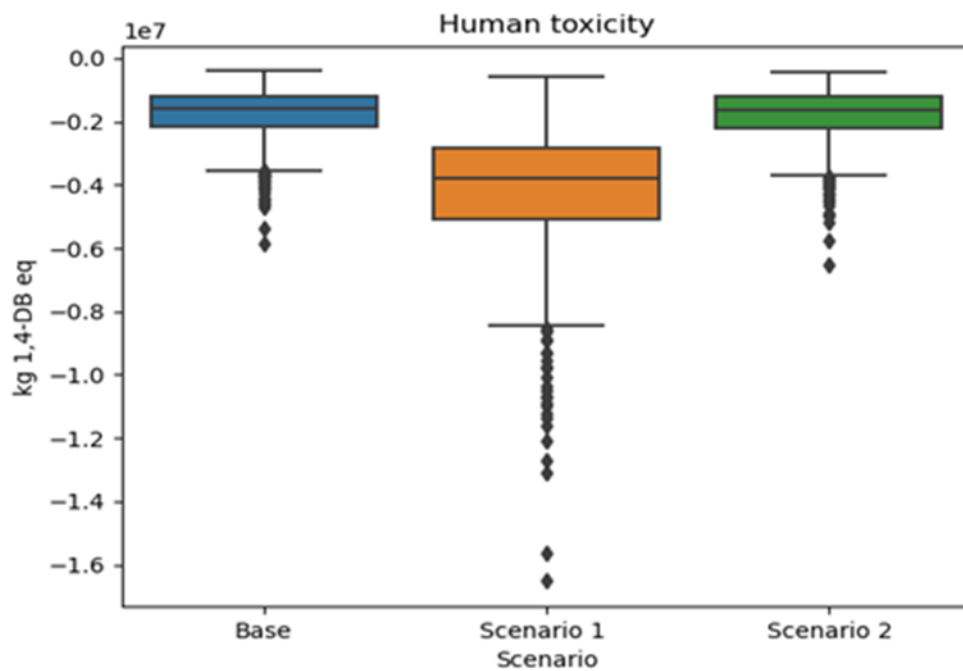
The Baseline scenario in Figure 4. 8 has a moderate median global warming potential but is associated with a significant amount of uncertainty and variability. Scenario 1 exhibits the most negative median global warming potential, suggesting a potentially higher impact on global warming. However, this scenario also has the largest uncertainty, indicating less confidence in the results. Scenario 2 has a less negative median global warming potential compared to Scenario 1 and a moderate standard deviation, implying a more stable and predictable outcome compared to Scenario 1.



**Figure 4. 8 uncertainty result in all scenarios for the global warming category**

**Human Toxicity potential**

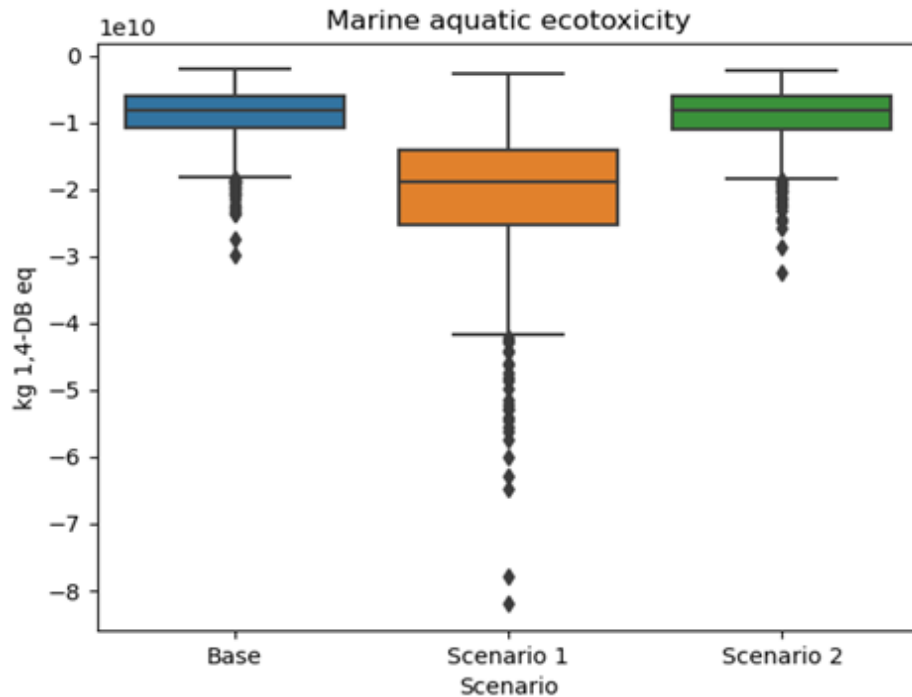
The Baseline scenario in Figure 4. 9 has a moderate median human toxicity potential but is associated with a significant amount of uncertainty and variability. Scenario 1 exhibits the most negative median human toxicity potential, suggesting a potentially higher impact on human health. However, this scenario also has the largest uncertainty, indicating less confidence in the results. Scenario 2 has a less negative median human toxicity potential compared to Scenario 1 and a moderate standard deviation, implying a more stable and predictable outcome compared to Scenario 1.



**Figure 4. 9 uncertainty result in all scenarios for the human toxicity category**

**Marine Aquatic ecotoxicity**

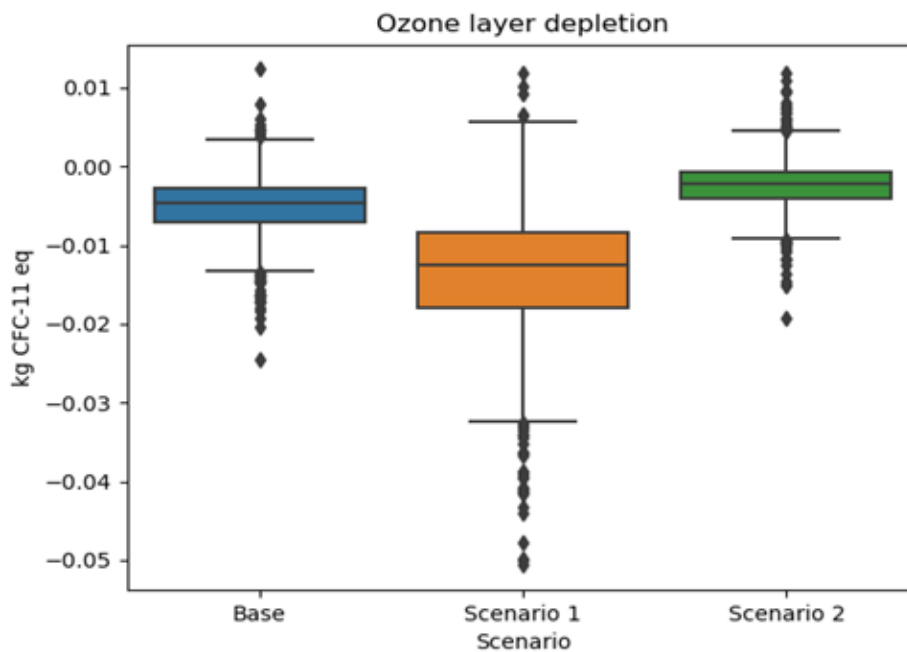
The Baseline scenario in Figure 4. 10 has a moderate median marine aquatic ecotoxicity toxicity potential but is associated with a significant amount of uncertainty and variability. Scenario 1 exhibits the most negative median marine aquatic ecotoxicity toxicity potential, suggesting a potentially higher impact on marine aquatic life. However, this scenario also has the largest uncertainty, indicating less confidence in the results. Scenario 2 has a less negative median marine aquatic ecotoxicity toxicity potential compared to Scenario 1 and a moderate standard deviation, implying a more stable and predictable outcome compared to Scenario 1.



**Figure 4. 10 uncertainty result in all scenarios for the marine aquatic ecotoxicity category**

### Ozone layer depletion

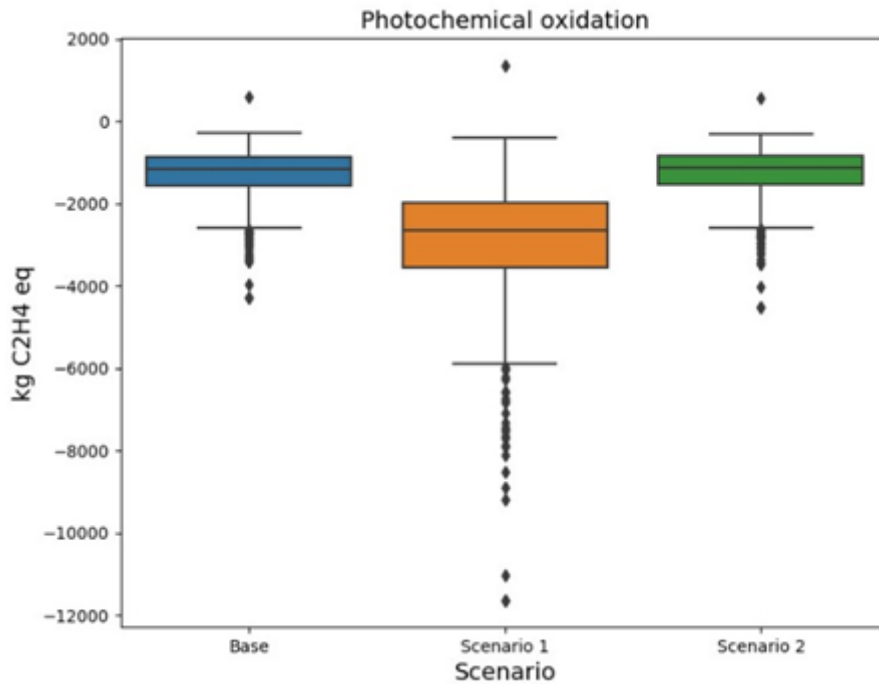
The Baseline scenario in Figure 4. 11 has a moderate median ozone layer depletion ecotoxicity toxicity potential but is associated with a significant amount of uncertainty and variability. Scenario 1 exhibits the most negative median ozone layer depletion ecotoxicity toxicity potential, suggesting a potentially higher impact on ozone layer depletion. However, this scenario also has the largest uncertainty, indicating less confidence in the results. Scenario 2 has a less negative median ozone layer depletion ecotoxicity toxicity potential compared to Scenario 1 and a moderate standard deviation, implying a more stable and predictable outcome compared to Scenario 1.



**Figure 4. 11 uncertainty result in all scenarios for the ozone layer depletion category**

### **Photochemical Oxidation**

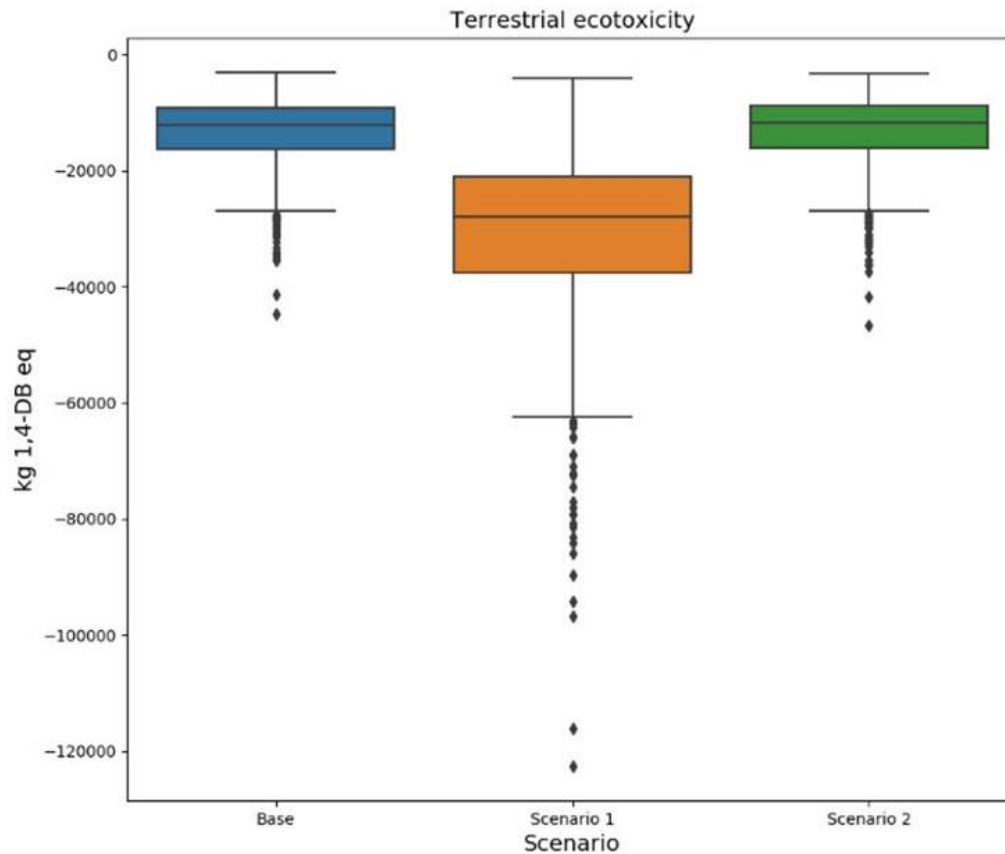
The Baseline scenario in Figure 4. 12 has a moderate median photochemical oxidation potential but is associated with a significant amount of uncertainty and variability. Scenario 1 exhibits the most negative median photochemical oxidation potential, suggesting a potentially higher impact on photochemical processes in the atmosphere. However, this scenario also has the largest uncertainty, indicating less confidence in the results. Scenario 2 has a less negative median photochemical oxidation potential compared to Scenario 1 and a moderate standard deviation, implying a more stable and predictable outcome compared to Scenario 1.



**Figure 4. 12 uncertainty result in all scenarios for the photochemical oxidation category**

### Terrestrial ecotoxicity

From Figure 4. 13, Scenario 1 exhibits the most negative median terrestrial ecotoxicity potential, suggesting a potentially higher impact on terrestrial ecosystems. However, this scenario also has the largest uncertainty, indicating less confidence in the results. Scenario 2 has a less negative median terrestrial ecotoxicity potential compared to Scenario 1 and a moderate standard deviation, implying a more stable and predictable outcome compared to Scenario 1.



**Figure 4. 13 uncertainty result in all scenarios for the terrestrial ecotoxicity category**

The Monte Carlo simulation results indicates that the quantity uncertainty of the LCA results is mainly influenced by the data reliability and temporal correlation of the LCI data. The background data, which are often based on qualified estimates from outdated datasets, introduce a large amount of uncertainty in the assessment. This finding is consistent with Bamber et al., (2020), who emphasized the need for comprehensive uncertainty analysis in LCA studies to enhance the robustness and validity of the results. The uncertainty can be reduced by using more recent and reliable data, updating, and validating the data regularly, and integrating and verifying different data sources.

## CHAPTER FIVE

### SUMMARY, RECOMMENDATION AND CONCLUSION

#### 5.1 Conclusion

Anaerobic digestion systems have demonstrated their ability to convert municipal solid waste into valuable energy resources, making them a promising environmentally sustainable energy solution. For a total of 3,800 tons of biowaste and 1,400 tons of freshwater, the system generates 314,484 kWh/year of electricity, equivalent to 352,589 Nm<sup>3</sup>/year of biogas. The life cycle inventory revealed that greenhouse gas emissions, including CH<sub>4</sub> (3,786.8 kg), NO<sub>x</sub> (1614.48 kg), and N<sub>2</sub>O (12.79 kg), contribute to the carbon footprint. These values show that the system has a lower environmental impact than conventional electricity generation from fossil fuels, which emit more CO<sub>2</sub> and other pollutants. Environmental benefits were observed in various impact categories, except for abiotic depletion, and the transportation stage had the highest contribution to the environmental impact of the anaerobic digestion system. The carbon footprint can be further reduced by optimizing the biogas utilization and minimizing the transportation distance and fuel consumption.

The sensitivity analysis highlighted the trade-offs between emission savings and increased burdens in different scenarios, emphasizing the system's potential for sustainable energy. Sensitivity analysis indicated that replacing solar PV electricity with Ghana's electricity production mix led to a substantial reduction in the abiotic depletion category (-99.61%) but resulted in increased burdens, notably acidification (725%). Scenario 2, involving the use of biogas engine electricity (CHP), demonstrated emission savings across most impact categories, except for human toxicity and marine aquatic ecotoxicity. The highest reduction was observed in ozone layer depletion (-2637%), whereas human toxicity showed a slight increase (0.55%). These values show that the system's environmental performance is highly dependent on the choice of electricity source and that solar PV electricity is preferable to Ghana's electricity mix

in terms of reducing most environmental impacts. However, biogas engine electricity (CHP) offers an even better alternative, as it can utilize the biogas produced by the anaerobic digestion system and generate both electricity and heat, thus increasing the system's efficiency and reducing its emissions. Therefore, the sensitivity analysis suggests that the system can be optimized by adopting biogas engine electricity (CHP) as the main electricity source and using solar PV electricity as a backup or supplementary source.

In addition to the sensitivity analysis, the uncertainty analysis revealed that data reliability and temporal correlation play significant roles in quantity uncertainty. Background data, often based on qualified estimates from datasets dating back six years or more, contribute to the uncertainty in the assessment. Despite these uncertainties, this work demonstrated that electricity generation from anaerobic digestion of MSW is a promising environmentally sustainable energy solution that can support the transition to a low-carbon economy and mitigate climate change by transforming waste into clean energy.

## **5.2 Recommendations**

The main limitation of this study is the unavailability of data in databases for the Ghana scenario. The lack of a national life cycle inventory database also created uncertainty in the present study. With a more comprehensive database, further studies can cover a wider scope of impact assessments. Other studies can take the lead from this and examine the socioeconomic impacts of adopting an anaerobic digestion system as a renewable energy source. Based on the findings of this study, programs and policies that seek to promote the adoption of an anaerobic digestion system as an alternative to renewable energy sources and a viable waste management approach are recommended. Policy actions include the provision of incentives, subsidies, and regulatory frameworks that promote the development and implementation of anaerobic digestion projects for waste management and renewable energy generation.

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## APPENDIX

<b>1. Municipal Solid Waste Transport</b>				
<b>Inputs</b>	<b>Units</b>	<b>Value</b>	<b>Data Quality</b>	<b>Uncertainty</b>
Municipal Solid Waste	tonnes	8,615.00		
transport, freight, lorry	t*km	86,150.00	2, 1, 4, 2, 1	1.59
<b>Outputs</b>	<b>Units</b>	<b>Value</b>	<b>Data Quality</b>	<b>Uncertainty</b>
Municipal Solid Waste Transported	tonnes	8,615.00		
<b>2. Waste Segregation</b>				
<b>Inputs</b>	<b>Units</b>	<b>Value</b>	<b>Data Quality</b>	<b>Uncertainty</b>
Municipal Solid Waste Transported	tonnes	8,615.00		
Electricity (solar PV)	kWh	48,180.00	2, 1, 4, 1, 2	1.64
<b>Outputs</b>	<b>Units</b>	<b>Value</b>	<b>Data Quality</b>	<b>Uncertainty</b>
Organic Waste (OFMSW)	tonnes	3,800.00		
<b>3. Anaerobic Digestion</b>				
<b>Inputs</b>	<b>Units</b>	<b>Value</b>	<b>Data Quality</b>	<b>Uncertainty</b>
Organic Waste (OFMSW)	tonnes	3,800.00		
Fresh Water	tonnes	1,400.00	2, 1, 1, 1, 1	1.54
Electricity (solar PV)	kWh	314,484.00	2, 1, 4, 1, 2	1.64
<b>Outputs</b>	<b>Units</b>	<b>Value</b>	<b>Data Quality</b>	<b>Uncertainty</b>
Biogas from Biowaste	Nm <sup>3</sup>	352,589.00		
Digestate	tonnes	8,556.00	2, 1, 1, 1, 1	1.54
Methane, non-fossil	kg	3,786.80	3, 1, 1, 3, 1	1.62
<b>4. Electricity Generation</b>				
<b>Inputs</b>	<b>Units</b>	<b>Value</b>	<b>Data Quality</b>	<b>Uncertainty</b>
Biogas from Biowaste	Nm <sup>3</sup>	352,589.00		
<b>Outputs</b>	<b>Units</b>	<b>Value</b>	<b>Data Quality</b>	<b>Uncertainty</b>
Avoided heat	kWh	868,621.00	2, 1, 1, 1, 1	1.54
Electricity, from CHP	kWh	805,574.00	2, 1, 1, 1, 1	1.54
N <sub>2</sub> O (CHP)	kg	12.79	3, 1, 4, 4, 1	1.68
NOx (CHP)	kg	1,614.48	3, 1, 4, 4, 1	1.68

Figure A. 1 Life Cycle Inventory Data with uncertainty values

Ciroth et al. 2016					
Uncertainty Factors					
Indicator score	1	2	3	4	5
Reliability	1.0	1.54	1.61	1.69	25.0
Completeness	1.0	1.03	1.04	1.08	25.0
Temporal correlation	1.0	1.03	1.1	1.19	1.29
Geographical correlation	1.0	1.04	1.08	1.11	25.0
Further technological corre	1.0	1.18	1.65	2.08	2.8
Pedigree Matrix					
Indicator score	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sited relevant for the market considered, over an adequate period even out normal fluctuations	Representative data from >50 % of the sites relevant for the market considered, over an adequate period to even out normal	Representative data from only some sited (<<50 %) relevant for the market considered or >50 % of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference of the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different	Data from processes and materials under study from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

Figure A. 2 Data Quality Pedigree Matrix scores

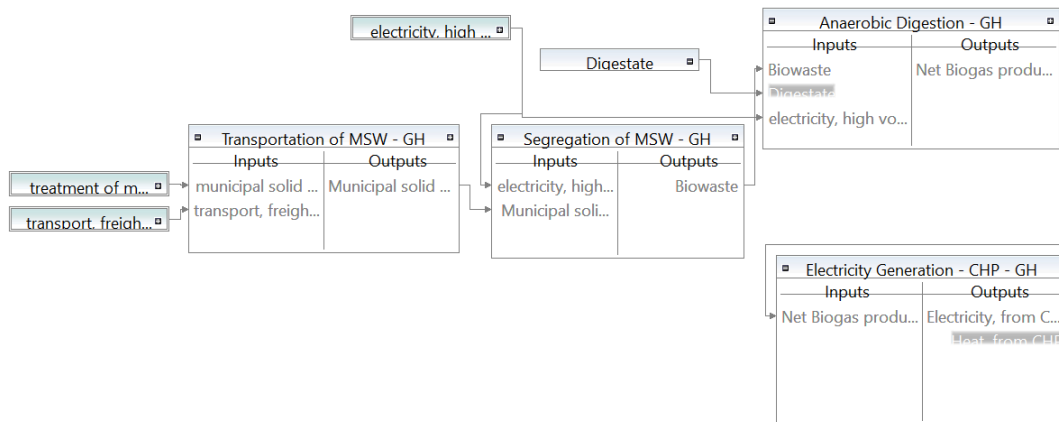


Figure A. 3 Model Graph of Biogas Plant in OpenLCA