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TITLE:

Evaluating And Comparing the Global Warming Potential From Black Soldier Fly Bioconversion of Faecal Matter, Pig Manure and Chicken Manure

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DECLARATION AND RECOMMENDATION

This thesis is my original work and has not been presented for a master's degree in any other university.

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This is to certify that the thesis entitled **"Evaluating and Comparing the Global Warming Potential From Black Soldier Fly's Bioconversion Of Faecal Matter, Pig Manure and Chicken Manure**" submitted in partial fulfillment of the requirements for the degree of Master of Science in Water Policy, the Graduate Program of the **Pan Africa Institute for Water and Energy Sciences (incl. Climate Change),** and has been carried out by Virginia Wamboi Gacuthi Id. **No PAUWES/2023/MWP01**, under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence hereby can submit the thesis to the Water Program for defense.

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DEDICATION

This thesis is dedicated to God for his favor and grace throughout. It is also dedicated to my father Samuel Gacuthi Kinyua, my mother Esther Wanjiku Kinyua, my family at large, and my friends for their immense support during my academic journey.

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviations	Description
AD	Anaerobic Digestion
ADC	Alternative Direct Current
BSF	Black Soldier Fly
COTEC	College of Engineering and Technology
DC	Direct Current
DOAS	Differential Optical Absorption Spectroscopy
GC	Gas Chromatography
GC-MS	Gas Chromatography Mass Spectroscopy
GC-FID	Gas Chromatography Flame Ionization Detector
GHGs	Greenhouse Gases
GWP	Global Warming Potential
IRGA	Infrared Gas Analyzer
IPCC	Intergovernmental Panel on Climate Change
JKUAT	Jomo Kenyatta University of Agriculture and Technology
LCA	Life Cycle Assessment
LUCF	Land-Use Change and Forestry
MS	Mass Spectroscopy
SDG	Sustainable Development Goal
PPM	Parts Per Million
RS	Sensor Resistance
UNEP	United Nations Environment Program
SWEED	Soil, Water and Environmental Engineering Department
USAID	United States Agency for International Development
USD	United States Dollar
VC	Voltage Circuit
UV	Ultraviolet
VRL	Voltage at the Load Resistor
WRI CAIT	World Resources Institute Climate Analysis Indicators Tool

ABSTRACT

Global warming, climate change and water pollution have become pressing environmental concerns worldwide. By 2050, the world's population is expected to grow from 7.8 billion in 2020 to 9.9 billion people, generating more waste. The improper disposal of the organic waste has profound impact on the water quality in Nairobi's River since they end up in open drains and waterways leading to elevated levels of nutrient such as phosphorus, which promotes and degrade aquatic ecosystems. This waste also results in increased greenhouse gases (GHGs) emissions into the atmosphere. Currently, in Kenya, the organic waste management, including faecal matter (FM), pig manure (PM), and chicken manure (CM), poses a significant challenge in the context of water pollution, global warming and climate change. Hence, this problem pertains to the need for an efficient way and cost-effective technology to manage waste that ultimately reduces the global warming potential (GWP). This research aimed to assess the global warming potential of the black soldier fly's bioconversion of faecal matter (FM), pig manure (PM) and chicken manure (CM). It adopted Black soldier fly larvae (BSFL, *Hermetia illucens*) technology, which is environmentally friendly as it mitigates the amount of greenhouse gases released in the atmosphere because of its quick bioconversion rate, good sustainability, and low cost-effectiveness. The set-up was in a greenhouse tunnel at the Department of Soil, Water and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology (JKUAT). The study used the MQ4 and MQ135 sensors to measure in real time the concentration of methane (CH_4), carbon dioxide (CO_2), Nitrous oxide (N_2O), and ammonia (NH_3) emitted during the bioconversion process. A comparison of the concentration of gas emissions from the bioconversion of the three substrates was studied. Finally, the Life Cycle Assessment (LCA) of BSFL during bioconversion of the FM, PM and CM was undertaken. The data was analyzed using R Studio 4.3.3 software for graphical visualization of GHGs concentrations and OpenLCA software for the LCA of the gases. The total GWP values were: as follows: 0.194 kg CO_2-eq (CM), 0.072 kg CO_2-eq (FM), 0.005 kg CO_2-eq (PM), 0.011 kg CO_2-eq (BSFCM), 0.006 kg CO_2-eq (BSFFM) and 0.001kg CO_2-eq (BSFPM). CM had the highest GWP, FM had a notable GWP while PM recorded the lowest GWP. BSFL bioconversion process can be used to manage organic waste from the environment while at the same time mitigating the GHGs emissions. The study suggests that large-scale adoption of BSFL as a climate-smart waste management solution can be promoted by developing supporting policies and regulatory frameworks. Additionally, various governments should provide incentives to enhance awareness campaigns and training programs to educate waste producers, farmers and industries to effectively contribute to the advancement of the circular economy.

Key Words: Global Warming Potential, Black Soldier Fly, Faecal Matter, Chicken Manure, Pig manure, Life Cycle Assessment, Greenhouse Gases

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Global warming and climate change have become pressing environmental concerns worldwide. Researchers have noted a warming trend that started over the past two or three centuries (Mawi, 2024). Global population growth has hastened the development of various industries in combination with industrialization, serving as the driver for economic growth and urbanization. By 2050, the world's population is expected to grow from 7.8 billion in 2020 to 9.9 billion, resulting in the generation of more waste (UN Habitat, 2022) . This means that there will be a corresponding increase in the emission of greenhouse gases into the atmosphere (Wang et al., 2021). The leading causes of global warming are related to human activities such as burning fossil fuels, deforestation, and tree-clearing, agricultural, farming activities, and inadequate waste management that release greenhouse gases into the atmosphere (Al-Yasiri & Géczi, 2021a).

Currently, world cities generate approximately 1.3 billion tons of solid waste per year and this volume is expected to increase to 2.2 billion tons by 2025 over a 69% increase in 10 years (Abubakar et al., 2022). According to the World Bank (2012), the rate of solid waste generation in lower-income countries will be more than double in the next 20 years. The yearly cost of solid waste management will rise globally from $205.4 billion in 2019 to over $375.5 billion in 2025 (Bhada-Tata, et, 2012). The economy, local and global environment, and health are greatly impacted by inappropriate waste management from the greenhouse gasses emitted. In most cases, these consequences come at a higher cost later than what it would have cost to handle the waste correctly in the first place (Raphela et al., 2024)

Sub-Saharan Africa produces over 62 million tons of waste annually. Although it varies greatly, ranging from 0.09 to 3.0 kg per person per day on average, per capita garbage generation in this region is relatively modest at 0.65 kilograms per day (Orhorhoro & Oghoghorie, 2019). Kenya produces an estimated 22,000 tons of solid waste each day, or 8 million tons yearly, based on an average of 0.5 kilograms of waste generated per person for the country's 45 million (Shahzad et al., 2023). It is estimated that urban areas generate 40% of the solid waste produced with a 10%

annual rate of urbanization, Kenya's urban population will produce an estimated 5.5 million tons as annually by 2030, which is three times more than what was produced in 2009 (Margareth, 2017). The improper disposal of the organic waste has profound impact on the water quality in Nairobi's River since they end up in open drains and waterways leading to elevated levels of nutrient such as phosphorus, which promotes and degrade aquatic ecosystems. A study done by Ngatia et al. (2023), revealed that raw sewage disposal, industrial activities, solid waste dumping and small-scale agriculture, had adverse effects on Ngong River's water quality. The study recommended for a need to closely monitor anthropogenic activities along Ngong River to reduce their probable pollution of the water in the river basin.

Figure 1.1: Faecal Sludge Being Deposited into the Nairobi River

To address the inadequate management of pig manure (PM), chicken manure (CM), and faecal matter (FM), which contribute to global warming by releasing greenhouse gases during bioconversion, an innovative sustainable approach of managing the solid waste needs to be embraced in Kenya and other parts of the world. The use of Black Soldier Fly Larvae (BSFL) technology has a high potential to cope with the current challenges related to inadequate reliable solid waste management infrastructure as it has favorable environmental and climate conditions. It is also capable of fostering regional growth, creating jobs, and local recycling of degradable waste and generating several products along the chain. This technology is eco-friendly as it mitigates greenhouse gas emissions given its efficient bioconversion rate, sustainability, and cost efficiency compared to the currently favored technologies, such as composting and landfilling, especially in Africa and Kenya at a larger scale (Salam et al., 2021).

1.2 Statement of the Problem

Kenya, like many other low- and middle-income countries, faces a challenge in the disposal of organic solid waste. The management of organic waste, including faecal matter, pig manure, and chicken manure, poses a significant challenge in the context of water pollution, global warming and climate change. The improper disposal of these waste possess serious public health, including outbreaks of waterborne diseases such as cholera, typhoid and also affects aquatic life and downstream water users (Sewe, 2022). The waste also contributes a substantial source of greenhouse gases. Apart from the land-use change and forestry (LUCF) sector, agriculture accounts for 62.8% of Kenya's total greenhouse gas emissions, cattle intestinal fermentation accounted for 55% of emissions, while manure left on pasture contributed 36.9% (USAID, 2013). The release of these greenhouse gases, such as methane, carbon dioxide, nitrous oxide and ammonia contribute significantly to global warming and climate change.

Kenya's economy is based primarily on agriculture; hence the country has been heavily impacted by the effects of global warming, including droughts and floods, on a large scale. According to the Institute of Economic Affairs (2022), drought had left 3.5 million people experiencing food insecurity, a 13% increase since February of the same year. This has led to decreased incomes for farmers, and increased reliance on food imports, placing a strain on the Kenyan economy. By 12 May 2024, over 380,000 people had been impacted by the floods, over 280,000 had been forced to relocate, over 260 people had died, 188 had been injured, and 75 were still unaccounted for. In addition, approximately 41,000 acres of agriculture were flooded and nearly 9,000 animals had been lost (UNOCHA, 2024).

The problem at hand pertains to the need for efficient way and cost-effective technology to manage manure and faecal matter that ultimately leads to the reduction of the greenhouse gases thus reducing global warming potential in Kenya.

1.3 Objectives

1.3.1 Main Objective

The main objective of this study was to evaluate and compare the Global Warming Potential (GWP) of black soldier fly's bioconversion of faecal matter, pig manure and chicken manure.

1.3.2 Specific Objectives

The specific objectives of this study were to:

a) Determine the concentration levels of greenhouse gases (methane, carbon dioxide, nitrous oxide, and ammonia) emitted during bioconversion of faecal matter, pig manure, and chicken manure by black soldier fly.

b) Compare the greenhouse gases produced from the faecal matter, pig manure, and chicken manure during bioconversion by black soldier fly larvae.

c) Undertake a lifecycle analysis assessment of gases emitted from bioconversion of faecal matter, pig manure, and chicken manure by black soldier fly and compare the global warming potential of treated waste.

1.4 Research Questions

a) What is the level of the greenhouse gases namely methane, carbon dioxide, nitrous oxide and ammonia emitted from the bioconversion of faecal matter, pig manure, and chicken manure during the rearing of black soldier fly larvae?

b) What are the overall greenhouse gas emissions associated with each pathway of the substrate uses as feedstock during bioconversion by black soldier Fly larvae?

c) What is the total global warming potential with the bioconversion process for each waste type used as substrate?

1.5 Justification of the Study

To fulfill Kenya's constitutional right to a clean and healthy environment for all, advance the circular economy to generate jobs and wealth from the waste sector, and further the country's sustainable development goals, it is essential that the waste management challenge in Kenya be effectively addressed. Improper management of waste poses a threat to the environment leading to climate change and eventually hindering the achievement of sustainable development goals, particularly Goal 11, which aims to make cities and human settlements inclusive, safe, resilient, and sustainable. Target 11.6 specifically focuses on reducing the adverse per capita environmental impact of cities, emphasizing the need for improved air quality and effective waste management by 2030. Findings of this study aided in managing waste, particularly chicken manure, pig manure and faecal matter which is a major problem in Kenya and other developing countries in general.

Kenya's contribution towards the achievement of the United Nations Sustainable Development Goal has become difficult. As a result, there is a need to develop ways how to reduce the amount of greenhouse gases that are released into the atmosphere while at the same time managing the associated waste. These findings can help in contributing to the achievement of various United Nations Sustainable Development Goals including but not limited to ensuring clean water and sanitation (SDG6), creating sustainable cities and inclusive communities (SDG11), and mitigating climate change (SDG13).

By employing the Black Soldier Fly Larvae bioconversion process, the environmental impact associated with these waste materials can be mitigated and their global warming potential reduced. More

1.6 Scope and Limitation of the Study

1.6.1 Geographical Scope

This research was carried out at Jomo Kenyatta University of Agriculture and Technology (JKUAT), College of Engineering and Technology (COTEC), Soil, Water and Environmental Engineering Department (SWEED and in the Chemistry laboratory in Kenya. The study was conducted under a controlled environment in a greenhouse tunnel at SWEED.

1.6.2 Content Scope

The study focused on concentration level of the greenhouse gases namely methane, carbon dioxide nitrous oxide and ammonia emitted from bioconversion of faecal matter, pig manure and chicken manure by black soldier fly. The overall greenhouse gas emissions and global warming potential associated with each pathway was estimated. Lastly, the resultant total global warming potential with the bioconversion process for each waste type of faecal matter, pig manure and chicken manure were determined.

1.6.3 Time Scope

The study was conducted for five months, from mid November 2024 to end of March 2025. The data was collected physically using real-time sensors for measurement of the greenhouse gases concentration emitted and laboratory analysis of samples.

1.6.4 Limitations

The primary limitation of this research was that it did not analyze how temperature and humidity variations affects bioconversion process.

CHAPTER TWO

LITERATURE REVIEW

2.1 General Overview

Generally, waste is a concern in many regions globally. When not adequately managed, it endangers both public health and the environment in general. This escalating problem is closely tied to societal production and consumption patterns, impacting all individuals. Effective waste management is crucial towards supporting modern society, especially in urban regions, and is considered a fundamental utility service in the 21st century ("Glob. Waste Manag. Outlook," 2016). It is not only a basic human necessity but also can be seen as a fundamental human entitlement. Having adequate sanitation and solid waste management is vital to society and the economy. Unfortunately, society and the economy may suffer greatly if waste management is neglected or ignored. The production and makeup of waste vary across nations and even within regions of the same country, primarily due to differences in population size, levels of urbanization, standards of living, and economic prosperity (Gichamo & Gökçekuş, 2019).

2.2 Global Warming

Global warming refers to the gradual rise in the Earth's surface temperature, a phenomenon that has been observed over the last couple of centuries. This shift has disrupted the Earth's climate pattern (Abbass et al., 2022). Global Warming Potential (GWP) quantifies the impact of various gases, termed Greenhouse Gases (GHGs), on warming the Earth. Recent years' extreme weather has intensified discussions regarding the rise in Earth's temperature. As the Earth's temperature rises, occurrences of disasters such as hurricanes, droughts, and floods are becoming more frequent. In the past century, the average air temperature near the Earth's surface has increased by slightly under 1.0 degrees Celsius or approximately 1.3 degrees Fahrenheit (Venkataramanan & Smitha, 2011). Many regions and seasons have already witnessed warming that exceeds the global average, with land experiencing a greater increase in temperature on average compared to the ocean.

According to the Intergovernmental Panel on Climate Change report IPCC (2023), the global average temperature of Earth's surface would be about -18°C rather than the present average of 15°C.

The ongoing global climate change has been related to GHG emissions because of the atmospheric warming effects of these emissions. The main greenhouse gases (GHGs) contributing to climate change are CO_2, CH_4, and N_2O. To evaluate the impact of human activities on climate change, the carbon footprint is used as a key environmental indicator. Developed over the past decade, it quantifies the total GHG emissions generated by various human actions, helping to assess and mitigate environmental impact (El Geneidy et al., 2021). Based on the Parliamentary Office of Science and Technology, the carbon footprint represents the total CO_2 and other GHG emissions produced throughout the entire life cycle of a product or process (Azarkamand, 2020). Other GHGs are measured in carbon dioxide equivalents (CO_2eq), which are calculated by multiplying the mass of the gas (in tons) by its GWP over 100 years. CO_2 has a GWP of 1, while CH_4 has a GWP of 25, and N_2O has a GWP of 298 (Report & Horizon, 2021).

The concentration GHG measured in parts per million (ppm) can be converted into other units, such as mass or carbon equivalent, to facilitate emissions analysis and comparison. The gas concentration of CH_4, CO_2, N_2O, and NH_3 measured in ppm can be converted to mg/kg by the following formulae (K. & Boguski, 2008).

$$1\text{ppm} = \text{mg/kg} \tag{2.1}$$

Therefore,

$$1\text{ppm} = 0.001\ \text{g/kg}$$

$$1\text{ppm} = 0.000001\text{kg/kg}$$

2.2.1 Causes of Global Warming

Human activity is one of the main causes of global warming. In a report by the Intergovernmental Panel on Climate Change (IPCC), it is stated that human activities, primarily due to the release of greenhouse gases, have undeniably led to global warming (IPCC, 2023b). Between 2011-2020, the global surface temperature had risen by 1.1°C compared to the period between 1850 and 1900 (IPCC, 2023b). Greenhouse gas emissions worldwide have continued to rise, driven by unsustainable energy practices, changes in land use, lifestyles, consumption, and production patterns, both globally and within regions, countries, and among individuals (IPCC, 2023b). The combustion of fossil fuels for electricity generation, transportation, and various energy sectors stands as the primary contributor to GWP due to the emission of greenhouse gases, notably carbon dioxide (CO_2), which possesses high emission ratios (Al-Yasiri & Géczi, 2021b). Among other gases, fossil fuels release harmful air pollutants such as sulfur dioxide, nitrogen oxides, particulate matter, carbon monoxide, and mercury, posing risks to both the environment and human health (Azad, 2024).

Agriculture and farming serve as both a potential source and sink for greenhouse gases (GHGs) in the atmosphere. It acts as a source for three primary GHGs namely: carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) (Lenka et al., 2015). As per the Environmental Protection Agency's October 2020 report, researchers have determined that 37% of methane emissions resulting from human activity can be directly attributed to livestock rearing and agricultural practices. The overall emission of greenhouse gases (GHGs) from agriculture, encompassing livestock, is estimated to range between 25 and 32%, varying depending on the data source and the extent of land conversion for livestock-related activities (Chataut et al., 2023). In 2018, nitrogen fertilizer usage was accountable for around 10.6% of agricultural emissions and approximately 2.1% of total global greenhouse gas emission (Menegat et al., 2022).

2.2.2 Effects of Global Warming

The greenhouse effect is a natural process that has been occurring for millions of years, wherein certain gases in the atmosphere trap solar energy, leading to an increase in Earth's temperature. Sunlight reaches the Earth's surface, is absorbed by various elements, and then emitted back. While some energy escapes into space, a significant amount is retained due to greenhouse gases like water vapor, carbon dioxide, nitrous oxide, ozone, and methane (Buha, 2011).

Our global climate is changing quickly due to human activities, which is a factor in the frequency of extreme weather. The combustion of fossil fuels for electricity, heat, and transportation emits carbon dioxide, a greenhouse gas that traps solar radiation in the atmosphere. The extreme weather events include wildfires, hurricanes, wind storms, flooding, and droughts (Azad, 2024). Collectively, the costs of extreme weather events attributed to climate change from 2000 to 2019 are estimated at $2.86 trillion, averaging around $143 billion per year (Newman & Noy, 2023). Sea levels are rising globally because of glaciers and glaciers on land melting because of oceanic and atmospheric warming brought on by climate change. Since the late 1800s, sea levels have increased by roughly 0.22 meters, which has resulted in an increase in the frequency of flooding, hazardous storm surges, and saltwater intrusion (Azad, 2024). A recent study has revealed concerning forecasts for global economies, projecting losses exceeding $1 trillion by the end of the century due to the repercussions of rising sea levels on coastal cities (Adom, 2024).

2.2.3 Greenhouse Gases

Any gas that absorbs heat or infrared radiation from the Earth and keeps it from being released back into space is considered a greenhouse gas. Global temperature and weather patterns can be greatly impacted by even small changes in these gases' concentration throughout time. While some greenhouse gases occur naturally, human activities particularly fossils fuel, combustion, industrial processes and large scale agriculture have led to their increased especially since the industrial revolution (Filonchyk et al., 2024). Each gas differs in its Global Warming Potential (GWP), with methane and nitrous oxide being significantly more potent than CO_2 over shorter time frames. The accumulation of these gases enhances the "greenhouse effect," leading to global warming and widespread climate change impacts (J. Li et al., 2025). Chlorofluorocarbons (CFCs), methane gas, water vapor, CO_2, and ozone are a few significant GHGs. Global warming, or the "greenhouse effect," is caused by greenhouse gases and results in a net rise in the temperature of the Earth's atmosphere (Devine & Devine, 2024). Some these gases are presented in Table 2.1.

Table 2.1: Greenhouse Gases

Greenhouse Gas	Major Characteristics	Gas Concentration in the Atmosphere	References
Carbon Dioxide	Released due to human activities like the combustion of coal, oil, and natural gas it's represented by the chemical formula CO_2. It absorbs and radiates heat. It is 1.53 times denser than air	The concentration of CO_2 in biomass varies between 5 and 15%, depending on the type of fuel used and the combustion process employed. CO_2 concentration in the atmosphere is 421ppm Permissible limit 400 ppm	Poyet, 2021 IPCC 2023a
Nitrous Oxide	The main source is biological processes. Chemical formulae N_2O It is a colorless, odorless gas. It exhibits a global warming potential 310 times that of CO_2	Concentration in the atmosphere is 336 ppb in 2022. It exhibits a global warming potential 310 times that of CO_2 Permissible limits 100 ppm	C. Wang et al., 2021 Gulev et al. 2021

Ozone	It is an extremely reactive gas that's made up of three oxygen atoms. It is a man-made product that naturally occurs in the Earth's upper atmosphere. Its density is 1.5 greater than that of air It creates a protective layer that shields the Earth's surface from harmful ultraviolet (UV) light.	The average ozone concentration in Earth's atmosphere is about 0.3 ppm.	Grignani et al., 2021
Methane	Composed of one carbon atom bonded to four hydrogen atoms (CH_4). It a colorless and odorless at room temperature Has a density of 0.656kg/m^3 making it lighter than air	Methane levels averaged 1,895. Ppb during 2021, and around 162% greater than pre-industrial levels. It has a concentration of 1.8 ppm in the atmosphere. Permissible limit 1000	Van Amstel, 2012) IPCC, (2023a),

2.3 Methods of Natural Waste Management

Developing nations utilize inadequate methods for managing municipal waste, resulting in waste collection rates dropping below 70%, despite the growing rate of waste generation (Shumo, 2020). In Kenya, the problem of solid waste management is particularly prevalent in the big cities due to inadequate waste disposal systems, resulting in much of the waste being left uncollected on the streets. Open dumping practices are dangerous methods of waste disposal, as they allow waste to accumulate in the environment. This accumulation contributes to global warming by emitting carbon dioxide and other greenhouse gases (Rosalinda, 2019). Various natural methods for managing solid waste include composting, anaerobic digestion, and bioconversion by use of insects that are ferocious eaters like Black Soldier Fly Larvae (BSFL).

2.3.1 Composting

Composting is a natural phenomenon where organic matter undergoes a transformation into a nutrient-rich soil substance known as compost. This breakdown is facilitated by various microorganisms like bacteria, fungi, insects, and worms, as well as chemical reactions. Heat is produced during the process, and the more heat produced, the faster the decomposition process (bidin A, 2017).

There are two categories of composting which are anaerobic and aerobic. Aerobic composting involves the use of oxygen and is the most common method. Hassan et al. (2023) describe how food waste, such as leftovers, is often composted through anaerobic composting, which does not require oxygen. Despite the benefits of composting as a waste management technique, several challenges have been identified, including the release of CO_2, a greenhouse gas that contributes to climate change and biodiversity loss (Ayilara et al., 2020). Anaerobic processes can also release hydrogen sulfide, causing unpleasant and potentially toxic odors. Proper gas management is essential to enhance the sustainability of these systems.

2.3.2 Anaerobic Digestion

Anaerobic digestion (AD) is a natural process where various microorganisms break down organic matter, according to the United States Environmental Protection Agency. Over time, this method has proven to be an effective solution for mitigating the environmental impacts of organic waste and contributing to the reduction of carbon dioxide emissions. Organic waste is first placed inside a sealed digester to start the aerobic digestion process. The AD process stops the growth of germs and traps carbon dioxide and methane to stop the release of greenhouse gases by placing huge volumes of biodegradable trash in a confined and regulated space. The microorganisms within the digester produce two beneficial products: digestate, which recovers valuable nutrients required for plant growth, and biogas, which is sustainable energy (Summary, 2023).

Although anaerobic digestion seems to be a good solution, it has some drawbacks that make it not to be implemented. It has low biodegradability, process inhibition, and digester toxicity and the major roadblock to its implementation is the challenge of economic viability (Uddin & Wright, 2022). Anaerobic digestion alone is not a sustainable primary energy source. To make it economically viable, it's essential to maximize the additional benefits it offers, such as stabilizing processes, optimizing the recycling of inorganic nutrients, reducing dependence on synthetic fertilizers, and generating revenue from the sale of liquid fertilizer and compost (Policastro & Fabbricino, 2023).

2.3.2.1 Greenhouse Gas Emissions from Natural Waste Management

Various studies have evaluated greenhouse gas (GHG) emissions from composting and anaerobic digestion of organic waste. A comprehensive review by Nordahl et al. (2023), revealed that N_2O is the dominant GHG emitted from well-aerated composting operations, especially for nitrogen-rich feedstock like manure contributing between 45-91% of total GHG emissions (GWP_{100}) basis. It also revealed that CH_4 emissions are mainly influenced by poor aeration, while N_2O emissions are driven by feedstock compositions, particularly volatile solids and prior anaerobic digestion. Additionally, the U.S. Environmental Protection Agency (EPA) reported that composting and anaerobic digestion at biogas facilities accounted for2.6% and 0.1% of waste sector emissions in 2021, respectively (Inventory of U.S. Greenhouse Gas Emissions and Sinks, 2021). Furthermore, a study done by Aguirre-Villegas & Larson, (2017) demonstrated that integrating anaerobic digestion in manure management can reduce GHG emissions from storage handling and process by over 50%. The study also revealed that depending on the practices and farm size, GHG emissions per ton of manure range from 2200 to 12,000 g CO_2-eq for collection, 200 to 2400 g CO_2-eq for transportation, 16,000 to 84,000 g CO2-eq for storage, and 16,400 to 33,500 g CO_2-eq for land-application.

2.3.3 Black Soldier Fly Larvae

The black soldier fly (BSF), scientifically known as *Hermetia illucens*, is a highly beneficial insect species with significant potential. The growing interest in using harvested BSF larvae stems from their promising role as a protein source for animal feed, offering a viable alternative to traditional feed options (Siddiqui et al., 2022). These larvae are well-known for their ability to transform organic waste into compost. Additionally, their biomass, which is rich in protein and fatty acids, can be harvested for various applications (Ewusie et al., 2019). BSF has increasingly been adopted for biological waste treatment due to its reputation as an eco-friendly and cost-effective method (Siddiqui et al., 2022). However, there is limited documentation on the environmental impact of BSFL in terms of greenhouse gas emissions during the bioconversion of different types of waste.

Black soldiers fly is of dipterean order *Stratiomyidae* and is found occurring within natural environments around the world within warm-temperate, tropical, and sub-tropical areas within latitudes of 40°S to 45°N thus displaying wide range where they occur (Dortmans, Diener, et al., 2017). BSFs are non-pest, wasp-like, adaptable insects that feed on decaying matter. They typically measure between 13 to 20 mm in length (Lievens et al., 2021). The life cycle of BSF comprises five primary stages, which include eggs, larvae, prepupae, pupae, and adult flies. Each stage of the black soldier fly's life cycle varies significantly in length. Overall, the life cycle of a black soldier fly typically spans on average between 40 to 43 days (Yang, 2022).

The beginning of a BSF life cycle is marked by the egg stage, which simultaneously signifies the end of the previous life stage. A female fly deposits a cluster of eggs, a process known as ovipositing, typically ranging from 400 to 800 eggs (Dortmans, Diener, et al., 2017). These are placed near decomposing organic matter, within small, dry, sheltered crevices. Shortly after laying the eggs, the female dies. Placing the eggs near decomposing organic matter ensures that the emerging larvae have immediate access to their first food source. The sheltered locations safeguard the eggs from predators and prevent dehydration caused by direct sunlight.

On average, the eggs hatch approximately four days later, giving rise to larvae that are initially only a few millimeters in size. These larvae immediately begin searching for food and feeding on the nearby organic waste. They consume the decomposing matter and gradually grow from their initial size to approximately 2.5 cm in length and 0.5 cm in width (Nairuti et al., 2021). Throughout this stage, they maintain a creamy coloration.

In optimal conditions with sufficient food of high quality, the larvae of the black soldier fly typically undergo growth for 14 to 16 days (Ferrarezi et al., 2016). However, BSF larvae are remarkably resilient and can prolong their life cycle in unfavorable conditions. This larval stage is crucial as it is the only period during which the BSF feeds (Siddiqui et al., 2022). During this developmental phase, the larvae accumulate adequate reserves of fat and protein, enabling them to transition into pupation. When they emerge as flies, they search for a mate, copulate, and then deposit eggs before the end of their life cycle.

After completing its fifth larval stage, its larva goes into its final larval stage, referred to as its prepupa stage. The larva changes by losing its mouth part to make room for its hook-shaped part, while its color changes to charcoal gray to brown coloration. The pupation stage is where its prepupa changes into its fly form (Dortmans, Diener, et al., 2017). Figure 2.1 shows the complete life cycle of a black soldier fly (Terrell & Ingwel, 2022).

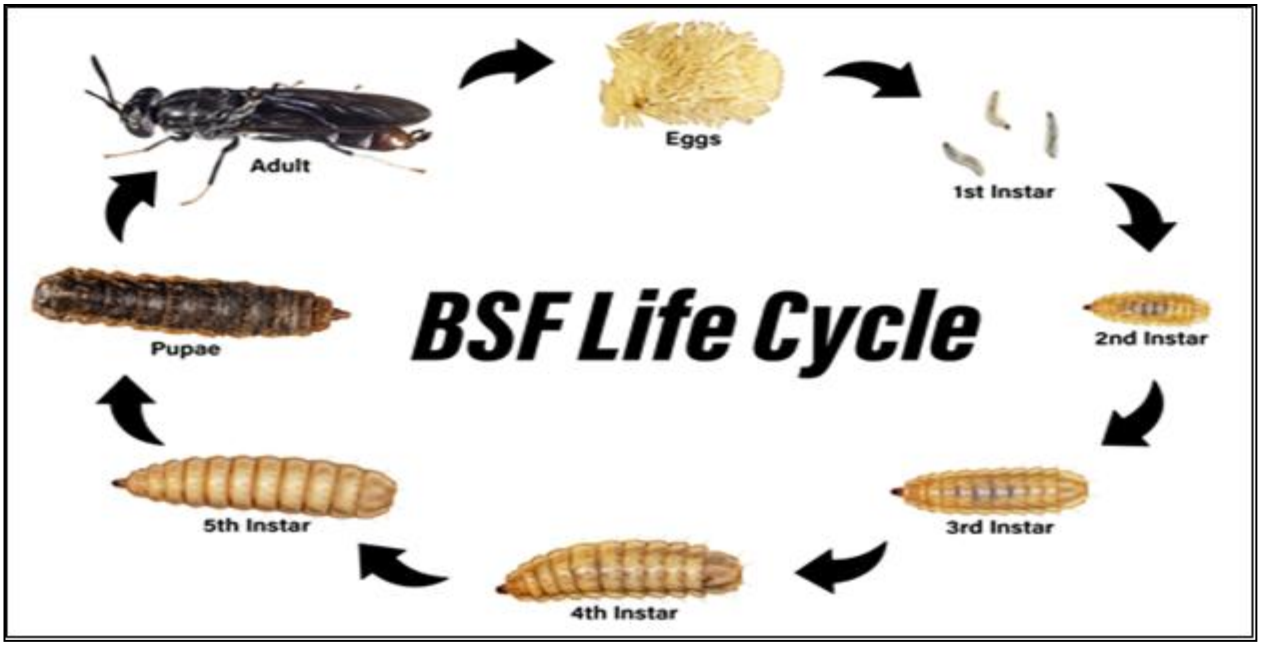

Figure 2.1: Life Cycle of a Black Soldier Fly

2.3.3.1 Benefits of Black Soldier Fly

The Black Soldier Fly has acquired significance as a matter of interest due to its role in waste management and sustainable agriculture. The insect can convert organic waste into useful protein and fat, hence emerging as a useful option to address issues of food safety and environmental challenges. The insect also helps to advance circular economy activities by including biological processes within modern agricultural programs.

(a) Biowaste Conversion

From the environmental health, functional benefits, and waste management perspectives, utilizing BSF in converting organic waste is of great benefit. Some of its benefits include its potential quick reduction of waste, its low footprints on carbon, effective body mass conversion of its feed, and also its non-disease-vector feature. It also helps control disease agents' population along with that of other pests (Siddiqui et al., 2022). From its business perspective, utilizing BSF is of great importance to its business returns. The process produces valuable products utilizing minimum water and land compared to its alternative of proteins. A study by (Pungavi, 2022), demonstrated that black soldier fly larvae (BSFL) have significant potential for recycling biological waste, converting 4 kg of garbage into approximately 800 g of larval biomass, achieving a waste reduction efficiency of 75%.

(b) Odour Reduction

Numerous environmental problems, such as greenhouse gas (GHG) emissions and the creation of toxic materials associated with existing disposal techniques like landfills and incineration, could be considerably reduced by BSFL (Kim et al., 2021)**.** It has been demonstrated that BSFL may efficiently reduce odorous chemicals found in dairy, swine, and poultry manures by at least 87% (Pungavi, 2022). This is yet another benefit of using BSFL as an eco-friendly waste management technique.

Black Soldier Fly Larvae (BSFL) are gaining global recognition as a promising waste management solution (Siva Raman et al., 2022). Their natural ability to break down organic waste makes them ideal for producing various commercial products, including animal feed, biodiesel, chitin-based biopolymers, and soil amendment by products. In many parts of the world, especially in developing countries, managing manure effectively remains a significant challenge. However, insect-based waste treatment offers a cost-effective and environmentally sustainable alternative (Purkayastha & Sarkar, 2022). According to a report by the United Nations Development Programme (2023), BSFL can process a wide variety of organic materials, including food waste, much faster than traditional composting methods, reducing waste volume by about 50% within a very short time.

This technology is environmentally friendly, as it lowers greenhouse gas emissions through its efficient bioconversion process, sustainability, and affordability (Salam et al., 2021). In one experiment, researchers combined different amounts of livestock manure with cow dung and rice bran as a co-substrate (Xiao et al., 2020). The results revealed that pig manure had a lower BSFL conversion rate compared to chicken manure, with pure chicken manure achieving the highest conversion rate of 15.31%. Adding cow dung to the mix further decreased the larvae's ability to convert both chicken and pig manure and did not improve the bioconversion of the combined substrate. This is due to cow dung lowered nutritional quality, altered microbial dynamics and created unfavorable growth conditions.

Another study conducted by Oyoo et al. (2023) investigated the co-treatment of faecal matter and kitchen waste using BSFL. Their research showed that the substrate containing 100% faeces performed the worst in terms of waste reduction, biomass conversion, and pre-pupal yield. Human faeces primarily consist of nutrient-poor food residues, which limit the larvae's performance. The best results were achieved when faecal matter was supplemented with 50% kitchen waste, resulting in more effective substrate reduction and increased biomass suitable for animal feed (Oyoo et al., 2023; Sibonje et al., 2024).

2.4 Life Cycle Assessment

The Life Cycle Assessment of BSF is employed to establish environmental costs and impacts of products that range from natural resources extraction through to waste disposal. Life cycle assessments of greenhouse gas emission are mostly part of overall environmental assessments that also take into account other environmental impacts or burdens (Reijnders, 2022).

Life cycle assessment can be divided into various phases. The four life cycle assessment phases are Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation for Improvement (Curran, 2017). The objective, aim, and boundary of the assessment are defined within the first stage, that is, goal definition. The second stage is composed of collecting data and calculating the costs and emission of each product-based process system. The real or potential environmental impacts are estimated by the impact assessment. The final stage of life cycle assessment is improvement assessment that identifies and estimates changes that need to improve the environment better (Iswara et al., 2020).

The LCA process can be categorized as either cradle-to-gate or cradle-to-grave depending on the scope. The life cycle is assessed by each stage of life, ranging from manufacturing of raw material (cradle) to end-of-life (grave), or by cradle-to-gate assessments where only a portion of LCA is analyzed (Mazuchi, 2018). For instance, the extraction of raw material up to manufacturing within the factory is analyzed by cradle-to-gate assessments (Kokare et al., 2023). This proves helpful in targeting life cycle stages that have significant effects on reductions of greenhouse gases and selecting key reduction actions. It can also assist in verifying claimed climate benefits and indicating key differences among alternative products (Numjuncharoen et al., 2015). LCA's findings can statistically forecast environmental impacts and their weights or values. Moreover, the results of the LCA are also displayed in the form of a graph that makes it simple to locate the hotspots. Therefore, this LCA function will facilitate users' identification of recommendations that will effectively mitigate the environmental impacts of its activities (Iswara et al., 2020).

A Life Cycle Assessment (LCA) on greenhouse gas emissions from irrigated maize found that farm activities contribute 36% of total emissions. However, farms that currently burn crop stubble could achieve a 30% reduction in cradle-to-farm emissions by switching to stubble incorporation instead (Grant & Beer, 2008). An analysis of LCA from beef production by (Beauchemin et al., 2010) Shows that most of the GHG emissions from beef production systems are from cow-calf herds, particularly from beef cows. The authors concluded that the facet of the beef production system deserves the highest emphasis in the search to reduce emissions from the feedlots if only they improve efficiency. A comparative life cycle assessment of three representative feed cereals showed that maize from class 300 had the highest environmental impact across all assessed categories, indicating the worst environmental profile. In contrast, cereals from classes 700 and 600 had the lowest impact in all categories, demonstrating the most favorable environmental profiles (Noya et al., 2015). Figure 2.2 presents the LCA processes from cradle-gate-grave.

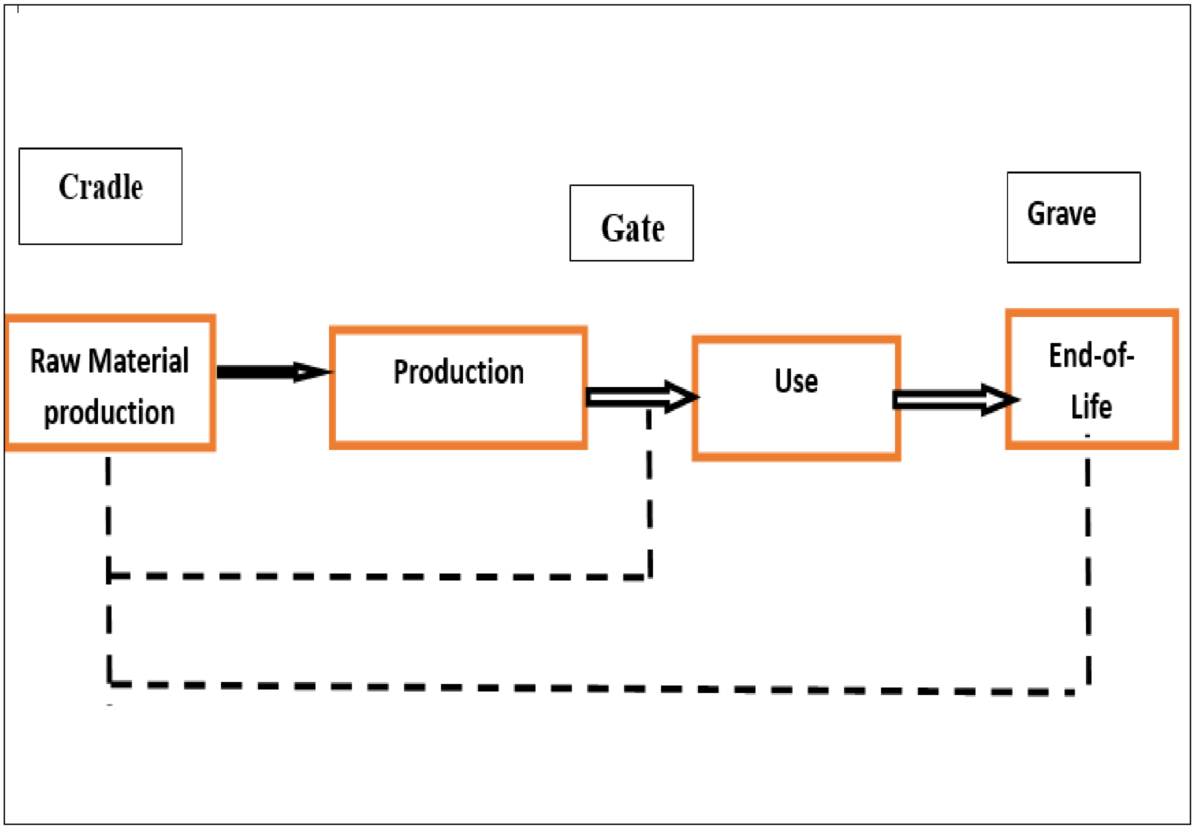

Figure 2.2: Life Cycle Assessment Process

2.4.1 Life Cycle Assessment Software

SimaPro by PRe-Sustainability, GaBi by PE-International, and OpenLCA by Khronos Group are a few of the well-known LCA software tools that researcher uses to perform LCA studies and evaluate the environmental impacts while making well-informed decisions. These softwares have a comprehensive life cycle inventory database along with life cycle impact assessment methodologies. It assists life cycle assessments by facilitating life cycle system modeling, environmental impacts, and compare assessments of scenarios (Arshad et al., 2023).

Simapro has been employed to make life cycle assessments of producing biodiesel using fish waste oil (Heidari-Maleni et al., 2024). Despite Simapro having good features to make LCAs, its weakness regarding flexibility, simplicity of implementing it, care of customers, handling of data, and cost can prove very troublesome to its customers (Z. Chen et al., 2024). Its weakness of simulating multi-supplier modeling within life cycle inventory (LCI) datasets and its need to make connective links among product modules are further constraints (Malu, 2024).

GaBi has been employed to make life cycle assessments of managing food waste using windrows and hybrid composting technology (Abu et al., 2021). It can also be able to model every element of a product or a system from a life cycle perspective allowing businesses to make informed decisions on the sustainability of their manufactured products. Though GaBi is a widely used LCA tool, it has weaknesses concerning flexibility, usability, cost, and accessing its datasets by its customers (Z. Chen et al., 2024). In addition, this software has a complex interface and a steep learning curve which can be daunting for beginners (Pauer et al., 2020).

Open LCA is a popular software application that is easy to use, freeware (open source), and allows users to calculate each stage of the life cycle assessment process (Silva et al., 2017). Another benefit of this application is that it gives users the ability to deal with many databases, including those that GaBi uses. Open LCA was first created to determine how items and procedures would affect the environment, but it may now also account for economic factors (Ormazabal et al., 2014). It also includes a feature-rich, current technical introduction to the software. Additionally, it offers the widest range of consistent, pertinent LCI and sustainability datasets in the world. Since 2006, GreenDelta has been developing OpenLCA with assistance from UNEP (United Nations Environment Programme), PRé Consultants (creators of SimaPro), and PE International (makers of GaBi). OpenLCA is accessible at various levels, including impact method database, project, product system, and process. Although the impact assessment technique package is free, OpenLCA does not come with it by default. It also processes networks and graphical modeling both automatically and manually (Iswara et al., 2020). Thus, this study conducted a Life LCA of BSFL bioconversion of faecal matter, pig manure, and poultry manure using OpenLCA software. The findings provided valuable insights to inform policymakers on waste management strategies that reduces GHG emission on the atmosphere.

2.5 Greenhouse Gas Detection Methods

Greenhouse gas monitoring devices use advanced tools to measure and track gases like CO_2, CH_4, and N_2O, which play a significant role in climate change. Some of the equipment used includes

Gas Chromatography Flame Ionization Detectors (GC-FID), Gas Chromatography-Mass Spectroscopy (GC-MS), Infrared Gas Analyzers, and Differential Optical Absorption Spectroscopy (DOAS). All of these devices are useful means of analyzing GHGs that contribute to climate studies and climate mitigation actions as presented in Table 2.2

Table 2.2: Greenhouse Gas Detection Methods

Analytical Technique	Gases analyzed.	Analytical principles	References
Differential Optical Absorption Spectroscopy (DOAS)	CO_2, CO, CH_4, N_2O,	This method works by measuring the amount of solar radiation absorbed by the atmosphere at specific wavelength ranges where the gas being studied has a clear and defined absorption cross-section. The device is pointed towards the zenith for stratospheric observations, typically during twilight.	(Schreier et al., 2015)
Infrared Gas Analyzer (IRGA)	NO, SO_2, CO_2, CO, CH_4, O_2	This method measures gas concentration by comparing how much-infrared light is absorbed as it passes through two gas sample cells. The sample cell is used to calculate the unknown sample gas concentration, while the reference cell is filled with a gas at a known concentration. By measuring the gas's absorption of a particular infrared wavelength, the concentration of the gas can be determined electrooptically.	(Borhan & Khanaum, 2022)
Gas Chromatography Flame Ionization Detector (GC-FID)	N_2O, CH_4, CO_2,	An FID ionizes organic molecules that contain carbon using a flame. Each analyte travels through a flame that is powered by hydrogen and zero air after the sample has been separated in the GC column, ionizing the carbon atoms. After forming, the ions are gathered and their current at the electrodes of the detector is measured. As the charged ions are gathered by the detector, current is generated. After that, the current is transformed into an electrical signal expressed in millivolts (mV) or picoamperes (pA)	(Shellie & Heng, 2023)
Gas Chromatography Mass	N_2O, CH_4, CO_2,	It uses variations in the ratios of charges to masses (mass/charge; m/z) to separate ionized particles, such as atoms, molecules, and clusters.	(Sugai, 2017)

Spectroscopy (GC-MS)	It can also be used to calculate the molecular weight of the particles.

2.5.1 Sensors for Greenhouse Gases

Various sensors have been developed to detect CO_2, CH_4, and N_2O, chosen for their key features such as sensitivity, selectivity, stability, accuracy, and low cost. Among these, instruments equipped with mass spectrometers are particularly effective because they respond rapidly, can detect multiple gases simultaneously, exhibit linear responses across a wide concentration range, and provide high accuracy and stability (Borhan & Khanaum, 2022).

2.5.1.1 Infrared Gas Analyzer (IRGA)

The amounts of different GHGs are measured using an infrared gas analyzer with a sensor. The reference chamber and the chamber that allows for the measurement of the type and quantity of gas are the two chambers that make up the fundamental design of an infrared gas analyzer. An infrared gas analyzer measures trace gases by determining how much of an emitted infrared light is absorbed by a specific air sample (Borhan & Khanaum, 2022). This method measures the gas concentration by comparing the absorption of infrared light that passes through two gas sample cells. The sample cell is used to calculate the unknown sample gas concentration, while the reference cell is filled with a gas at a known concentration. By measuring the gas's absorption of a particular infrared wavelength, the concentration of the gas can be determined electrooptically (Borhan & Khanaum, 2022). It focuses on infrared light source through a sample cell holding a continuously flowing sample of the gas mixture, and onto a detector after wavelength selection. The property of some gases to absorb unique light wavelengths can be used to detect the concentration of a selected gas in a mixture. The IRGA can measure the concentrations of NO, SO_2, CO_2, CO, CH_4, and O_2 components in a gas sample (Fiedler et al., 2022). Although it's sensitive to these greenhouse gases the sensors for infrared gases are gas specific. It has a gas curve and temperature compensation response of each detectable gas which are distinct. This kind of setting can lead to misleading readings from these gas detectors, which could create dangerous working conditions (Berman et al., 2012).

2.5.1.2 Differential Optical Absorption Spectroscopy (DOAS)

Modern techniques such as Differential Optical Absorption Spectroscopy (DOAS) are used to quantitatively analyze a wide range of trace gases in the environment by recording and evaluating the characteristic differential absorption of a visible light source over a path of several kilometers in the open atmosphere (Platt, 2017). Different studies have used DOAS in measuring of greenhouse gases like on differential optical absorption spectroscopy lidar for mid-infrared gaseous measurements (Lambert-Girard et al., 2015), direct absorption and photoacoustic spectroscopy for gas analysis by (Fathy et al., 2022). Despite its being widely used DOAS has several limitations which is not limited to long path length that cause complications when analyzing the results, set up of the remote receiving optics or reflector can be difficult, and also lack of accurate reference spectra can be a source of error too (Reiche et al., 2014).

2.5.1.3 MQ4 Sensor and MQ135 Sensor

The MQ series of gas sensors, including the MQ4 and MQ135, are designed to detect different types of gases. The MQ4 sensor, commonly used for methane detection in the 200–10,000 ppm range, operates with a 5V DC power source and uses tin dioxide (SnO_2) as a sensing element (Mukhtarov et al., 2024). The MQ4 sensor features a well-designed structure to ensure precise and accurate measurement. The sensor consists of a durable casing made of plastic and stainless-steel net, enclosing essential components including an AL_2O_3 micro-ceramic tube, a tin dioxide sensitive layer, a measuring electrode, and a heater (Sakayo et al., 2019). The heater is designed with precision to provide the ideal operating conditions for the sensitive components, ensuring that the sensor functions at the necessary temperature for precise and reliable measurements (Mukhtarov et al., 2024). The module is designed with six pins, with two specifically designated for supplying the required heating current, and the remaining four pins utilized for retrieving the sensor-generated signals. This pin configuration enabled efficient and dependable communication with external systems and devices (Singh et al., 2023). The sensor has digital and analog outputs. The digital output of the sensor is either high or low, based on a preset threshold value, while the analog output varies with gas concentration, because of its quick reaction time and great sensitivity to natural gas and methane. The MQ4 sensor is ideal for applications that require monitoring these gases (Winsen Electronics, 2018). Plate 2.1 shows the MQ-4 Gas Sensor.

Plate 2.1: MQ-4 Gas Sensor

The MQ135 gas sensor is specifically designed to detect a wide range of GHG gases. It is used to detect and measure CO_2, NH_3 and N_2O (Olimex, 2013). The sensor is equipped with an analog pin that connects to the microcontroller and a digital pin with a pot. This pin enables the measurement of gases in parts per million (ppm), providing precise data from the substrate being measured. This configuration enables the sensor to function independently, eliminating the requirement for a microcontroller for its operation (Neamah et al., 2020). Plate 2.5 shows MQ-135 Gas Sensor.

Plate 2.2: MQ-135 Gas Sensors

The detecting element of the gas sensor module is placed behind a steel exoskeleton. Through connecting leads, current is applied to this sensing element. The gases that approach the sensing element become ionized and are absorbed by it because of this current, which is referred to as a heating current. This change in resistance affects the current flowing through the sensing element (Gorakhpur, 2020). The fluctuation in resistance is closely linked to the concentration of the target gas in the surrounding area (Kalra et al., 2016). In the MQ135 sensor's library file, the gas concentration is measured in parts per million (ppm) and is calculated by:

$$ppm = a * (Rs/R0) -b \qquad (2.3)$$

Where a and b are the parameters for calculating ppm of CO_2 from sensor resistance which are considered in the header file. R0 is the sensor resistance at 100 ppm of NH_3 in clean air, and Rs is the sensor resistance in the presence of the target gases (M. C. Bhosale et al., 2023).

This study used MQ-4 and MQ-135 sensor because of its ability to detect specific gases. Both sensors are highly sensitive and have fast response times, which is crucial when measuring CH_4, CO_2, and N_2O. This sensor also provides both analog and digital outputs, making it very easy to integrate and interpret the data. Above all these sensors are cost-effective compared to other gas sensors making it effective for real-time data collection.

2.5.1.4 Calibration of Sensors

A calibration is a set of modifications made to a sensor or instrument to ensure that it operates as precisely or error-free as possible. Appropriate sensor calibration will produce precise readings, which enable effective process control(Quan, 2017). Hence the calibration of gas sensors such as the MQ-4 and MQ-135 is essential to ensure their accuracy and reliability in detecting gases. The calibration process typically involves two main steps, preheating and setting a baseline resistance. The sensors are allowed to preheat for at least 24 hours to allow the internal heating element to stabilize which ensures accurate reading (Kalra et al., 2016). Before measuring the gas concentrations, Ro which is the resistance of the sensor in clean air needs to be determined. This is done by placing the sensors in a controlled environment with known gas concentrations and recording the sensor resistance (Rs) in various conditions (M. Bhosale et al., 2023).The Rs/Ro ratio is then used to derive gas concentration values based on the sensor's datasheet calibration curve (Kobbekaduwa et al., 2021).

2.6 Summary of Literature Review and Research Gap

Current research on bioconversion of black soldiers have focused on nutrient in the residual material (Parodi et al., 2021); Carbon footprint of processing city market waste for animal feeds in Kampala Uganda (Pishgar-Komleh et al., 2022); Waste reduction and bioconversion of quail, chicken, and pig manure (Diola et al., 2024); Black soldiers fly as a potential innovative and environmentally friendly tool for organic waste management. However, limited research has been reported on how Black soldier Fly (BSF) can be used to mitigate greenhouse gases being emitted during bioconversion of waste. Studies have used gas chromatography flame ionization detector (GC-FID), Infrared Gas analyzer and differential optical absorption spectroscopy for greenhouse gas detection methods (Shellie & Heng, 2023; Borhan & Khanaum, 2022; Lambert-Girard et al., 2015).

Despite the growing interest in sustainable waste management and climate change mitigation, limited research has comprehensively evaluated and compared the global warming potential of black soldier fly larvae (BSFL) bioconversion across different organic waste streams, such as faecal matter, pig manure, and chicken manure. Existing studies primarily focus on the efficiency of BSFL in organic waste reduction and protein production, with minimal emphasis on its role in greenhouse gas (GHG) mitigation. Furthermore, there is a lack of standardized methodologies for accurately quantifying GHG emissions in BSFL bioconversion systems.

To address this gap, this study employs an innovative approach using MQ34 and MQ135 sensors to measure real-time GHG emissions during the bioconversion process. The findings of this study will optimize BSFL effectiveness in managing organic waste and ultimately mitigating the GHG emissions from this waste.

2.7 Conceptual Framework

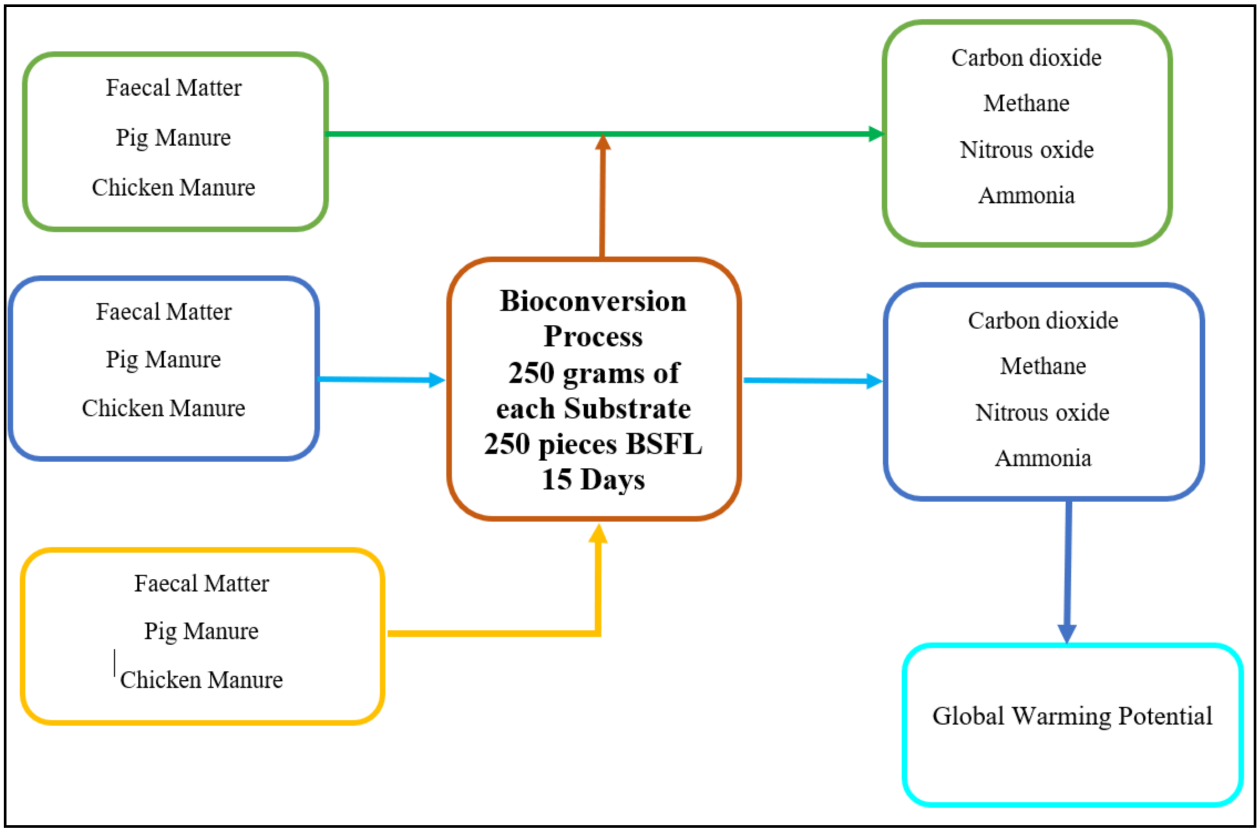

Figure 2.3: Conceptual Framework

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Location

This study was conducted in a greenhouse tunnel at Jomo Kenyatta University of Agriculture and Technology (JKUAT), Nairobi, Kenya. The geographical location map coordinates are -1.100396 (latitude) and 37.014533 (longitude). The experimental setup was done under a greenhouse tunnel while laboratory analysis was carried out in the Environmental Engineering and Chemistry laboratories respectively. Figure 3.1 presents a map of the study area.

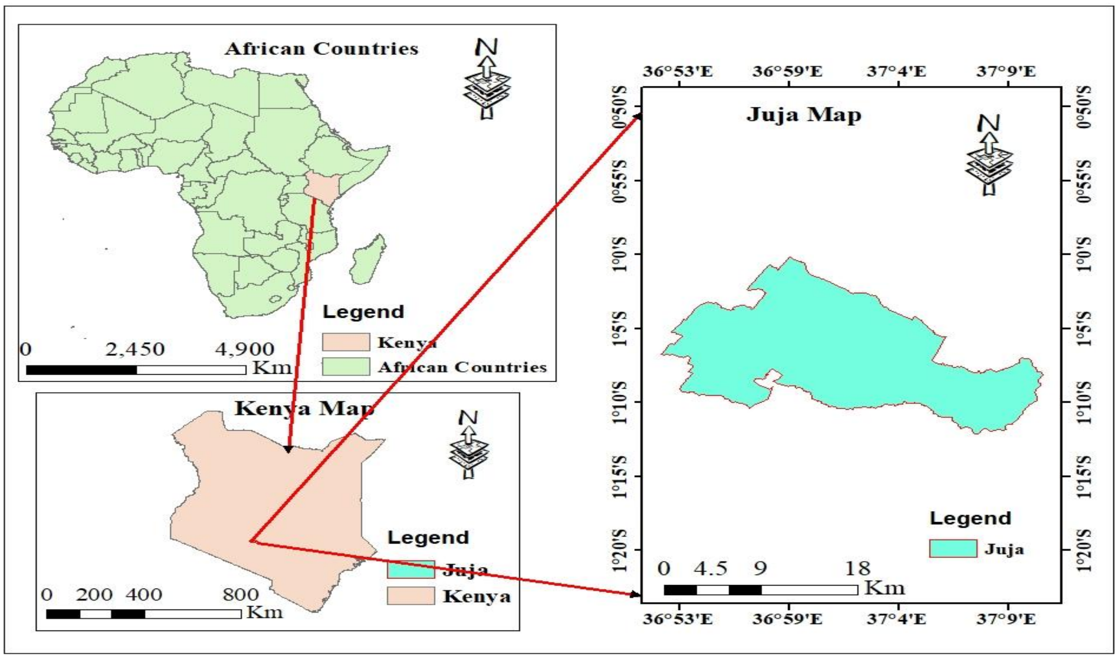

Figure 3.1: Map Showing Location of Study Area

3.1.1 Characteristics of Faecal Matter, Chicken Manure and Pig Manure

The elemental analysis of Faecal Matter, Chicken Manure and Pig Manure was conducted using a CHNS Organic Elemental Analyzer (Perkin Elmer 2400 Series II) according to procedure described by Firdaus et al. (2018). The elements (carbon, hydrogen, nitrogen, and sulfur) were expressed as a percentage of the total mass of the original sample. Ash content was determined based on an Oven Dry Weight (ODW) basis according to Equation 3.1 (Feng et al., 2005).

$$\%Ash = \frac{Weight_{Crucible\ plus\ ash} - Weight_{crucible}}{ODW_{sample}}\ x100 \qquad (3.1)$$

The oxygen content was then determined using Equation 3.2 (Ellison et al., 2023).

$$O = 100 - C - H - N - S - Ash \qquad (3.2)$$

3.2 Rearing of Black Soldier Fly

Black soldiers fly were reared according to the method highlighted by Dortmans et al. (2017). The eggs for the rearing of the black soldier fly were placed in cages with a suitable attractant medium that satisfied the fly requirements for egg deposition. After harvesting the eggs, they were removed from the cages after three days and placed into egg holders positioned over some chick marsh feed mixed with water as shown in Plate 3.1.

Plate 3.1 Eggs of Black Soldiers Over Chick Mash

This way, the hatchlings started feeding immediately after four days and dropped from the egg holders into the feed. The eggs hatched for three days, and the hatchlings continued constantly falling into the hatchling container where hatched larvae started feeding immediately. The hatching container was exchanged regularly to allow cohorts of young larvae of the same age to be together in each container. A high-quality food source of chicken feed for starter broiler chicks mixed with water was readily available to ensure fast growth of larvae. The feeding was done for 5 days using a mixture of 3.5 liters (L) of water and 2 kilograms (Kg) of chick mash.

3.2.1 Sensor Calibration

Before the sensors were inserted into the three plastic boxes containing the samples, calibration of the MQ4 and MQ135 sensors was done. The required components were ESP32, MQ4 and MQ 135, calibration gas cylinders, Resistors (for voltage divider, typically 10kΩ), multimeter and airtight chamber (for controlled gas exposure). The MQ4 and MQ135 sensors were allowed to stabilize by operating for 72 hours because metal oxide semiconductor gas sensor used required a burn-in period to ensure accurate and reliable readings. Proper ventilation was also ensured to prevent false reading. Baseline resistance was determined by exposing the sensors to clean, dry air and recording their analog output voltage (V_{out}). The sensor resistance (Rs) was then computed using the voltage divider equation.

$$Rs = \frac{(V_{cc} - V_{out}) * RL}{V_{out}} \tag{3.3}$$

Where:

V_{cc} = supply voltage (typically 5V)

V_{out} = sensor analog output voltage (volts)

RL = load resistance (typically 10kΩ)

Finally, the sensor resistance in clean air (Ro) was recorded, and the Rs/Ro ratio was calculated for gas concentration. The sensors were then calibrated using a known concentration of the target gas. To ensure stability, the sensors were allowed to equilibrate for 5–10 minutes before measurements were taken. After stabilization, the sensor's output voltage (V_{out}) and resistance (Rs) were recorded, and the Rs/Ro ratio was computed. The gas concentration was then determined using the sensor's datasheet, specifically by referencing the log-log graph provided. The attempt was done several times to improve the redesigning of the connections.

$$PPM = 10 \left(\frac{\log(R_S/R_o) - b}{m}\right) \tag{3.4}$$

Where:

PPM = gas concentration in parts per million

m = Slope

b = Intercept

m and b are sensor-specific values obtained from the datasheet.

MQ4 (Methane - CH_4)

m = -2.3

b = 0.72

Ro = 10kΩ

Rs = 1 kΩ

Therefore the formula was

$$PPM_{CH4} = 10^{\left(\frac{\log(R_S/R_O)-0.72}{-2.3}\right)} \tag{3.5}$$

MQ135 (CO_2, NH_3, NO_2)

For CO_2

m = -2.2

b = 0.42

Ro = 30kΩ

Rs = 2 kΩ

$$PPM_{C02} = 10^{\left(\frac{\log(R_S/R_O)-0.42}{-2.2}\right)} \tag{3.6}$$

Ammonia (NH_3)

m = -1.9

b = 0.53

Ro = 30kΩ

Rs = 2 kΩ

$$PPM_{NO3} = 10^{\left(\frac{\log(R_S/R_O)-0.53}{-1.9}\right)} \tag{3.7}$$

Nitrous oxide (N_2O)

m = -1.5

b = 1.05

Ro = 30kΩ

Rs = 5kΩ

$$PPM_{NO2} = 10^{\left(\frac{\mathrm{kg}(R_S/R_O)-1.05}{-1.5}\right)} \tag{3.8}$$

3.2.2 Levels of Greenhouse Gases Emitted from Bioconversion of the three Substrates

Faecal matter was collected from Gachororo Primary School, located at latitude -1.088352 and longitude 37.022607. Pig and chicken manure were purchased from one of the farmers in Juja. BSFL was collected from the colony on day 6 and starved for 24 hours before being introduced to the new feed. This starvation period ensured that their guts were emptied, minimizing the risk of carryover effects from previous feeds that could otherwise bias experimental results (Shishkov et al., 2019). 6-day-old BSFL were sampled by passing them through a 1.2 mm mesh screen (Nyakeri et al., 2019). Each treatment unit consisted of 250 pieces of seven-day-old larvae, which were fed 250 grams on waste of each respective substrate as a study done by (Vodounnou et al., 2024). There were six treatments done in triplicate hence a set-up comprising of a total of 18 treatment units as shown in the layout presented as Plate 3.2.

Plate 3.2. Experimental Setup

Sensors were used to measure temperature, humidity, NH_3, CO_2, NH_3 and N_2O concentration during the bioconversion. DHT22 sensor was used to measure temperature and relative humidity levels within the greenhouse. The recorded temperature ranged from a minimum of 15.8°C to a maximum of 46.1°C, while the relative humidity varied between 37.9% and 96.7%. The study compared emissions from the manure treated with BSFL and the controlled substrate which was left to decompose naturally.

Plate 3.3. A Set up of a Control Substrate and Feedstock Substrate

The GHGs produced from the three pathways were measured by the MQ4 sensor and MQ135 sensor. MQ4 was used to measure CH_4 produced and MQ135 was used to measure CO_2, NH_3, and N_2O produced. The sensors were installed on the three plastic boxes containing faecal matter, chicken manure and pig manure used as feedstocks respectively. The sampling process was conducted daily at an interval of 30 minutes from the three boxes for 15 days. Gas emitted in real time was recorded on an Excel sheet and was expressed in parts per million (ppm).

3.2.3 Data Analysis and Reporting

The sensors recorded the levels of GHG; CO_2, CH_4, NH_3, and N_2O emitted in real-time, after every 30 minutes over 15 days which marked a full growth cycle of the BSF. The average cumulative emissions of each gas per substrate were calculated daily using Excel for data analysis and comparison. The total cumulative emissions at the end of Day 15 were presented in a tabular format.

3.3 A Comparison of the Gas Emissions from the Bioconversion of the three Substrates

The MQ135 and MQ4 sensors had a data sheet sensor that recorded gas concentration on the Excel sheet. Cumulative emissions for each substrate CH_4, CO_2, NH_3 and N_2O were calculated using the Excel, based on data from three tests conducted for both the treated substrate with BSFL and the control. The sensors readings, recorded in parts per million (ppm), were analyzed to determine the standard deviation, providing insights into emission variability for each gas across different substrates. Finally, graphs were generated to compare emissions between the control and feedstock substrates. The pathway with the highest gas concentration was noted.

3.4 Data Analysis and Reporting

The statistical analysis of cumulative gas emitted (CO_2, CH_4, NH_3, and N_2O) for each substrate was conducted using RStudio software to compare emissions between control substrate and feedstock substrate. A line graph was generated using the ggplot2 package to visualize emission trends over the 15 days for each gas across the different substrates. To compare the average gas levels across different substrates and determine whether there were significant differences, a one-way Analysis of Variance (ANOVA) was performed.

3.5 Life Cycle Assessment for Black Soldier Fly Larvae from Bioconversion Process

Undertaking LCA requires four major things which include goal and scope definition, system boundary, life cycle inventory and life cycle impact assessment namely GWP. This study used the cradle to grave approach which provided a holistic view of black soldiers fly larvae environmental impacts throughout its entire life cycle.

3.5.1 Goal and Scope Definition

The goal of this study was to determine the environmental impacts of the bioconversion of the different rearing substrates using the BSFL through an LCA framework. Specifically, this study attempted to quantify the global warming potentials of BSFL during bioconversion of waste treatments. The scope of this LCA employed a cradle-to-grave framework that provided environmental impacts along each stage of the life cycle of BSFL, from substrate preparation up to final waste emission treatment.

3.5.2 System Boundary

The system boundary was the treatment facility where the bioconversion process occurred as shown in Figure 3.2. The treatment facility had two distinct stages: (1) stage of larval rearing and feeding, where chicken starter chick mash feed and water were provided to BSFL to promote rapid growth. For stage (2) of bioconversion, seven-old larval worms were introduced to three plastic containers of distinct feedstocks (faecal matter, chicken or poultry manure, pig manure). The products of this system were frass, NH_3, CO_2, CH_4, N_2O, and BSFL biomass.

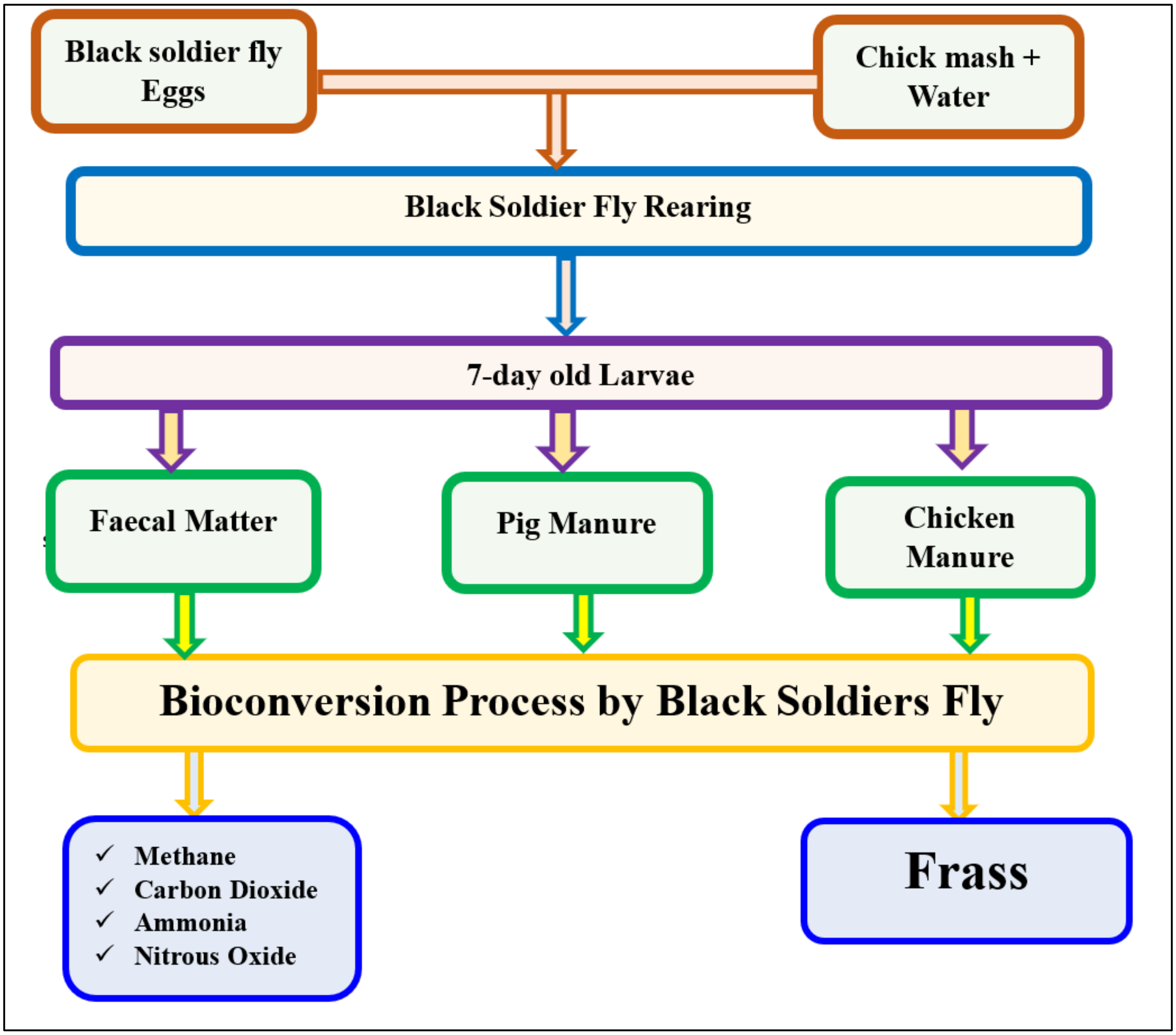

Figure 3.2: System Boundary

3.5.3 Life Cycle Inventory

The life cycle inventory (LCI) covered all the inputs, processes, and outputs within the system's boundaries. To assess the GHG emitted during the production of black soldier fly larvae (BSFL), both foreground and background data was used. The foreground data was gathered directly from the greenhouse at JKUAT, while the background data was sourced from the OpenCLA LCIA methods 2.4.0. Combining these sources gave a comprehensive understanding of the environmental impact of each feedstock. The functional unit of this study was the treatment of 250 grams of waste. The Global Warming Potential (GWP) was calculated using OpenCLA software.

3.5.4 Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) focused on calculating the GWP of the bioconversion process using OpenLCA software. The cumulative average gas emissions (CO_2, CH_4, NH_3, and N_2O) emitted during the bioconversion process converted from ppm to kg/kg was used as an input in OpenCLA software for the calculation of GWP expressed in CO_2-equivalents (CO_2-eq). This approach gave a clear picture of how much each feedstock contributes to climate change, making it possible to compare the environmental impacts of faecal matter, chicken manure, and pig manure. The results helped us identify which substrate had the lowest GWP, ultimately showing which one is the most sustainable choice for BSFL production and waste management.

3.5.5 Data Analysis and Reporting

The data was analyzed using OpenLCA software version 2.4 and the impact assessment method was sourced from the OpenLCA Life cycle impact assessment methods 2.4.0. It was then imported into the OpenLCA by navigating to the “File” menu and selecting “Import”. The flows were then created for each substrate defined all the inputs and the outputs. The inputs consisted of faecal matter, chicken manure, pig manure, chick mash feeds, and water, while the outputs consisted of CO_2, CH_4, N_2O, NH_3, BSFL biomass, and residual organic matter. Once the flows were ready, process was created by linking all the inputs and outputs. A new system boundary was defined to specify which substrate was being analyzed. The calculation was then run by selecting the appropriate settings. “None” was chosen as the allocation method, and IPCC 2021 was selected as the impact assessment to focus on the GWP. Finally, “Finish” was clicked to compute the GWP results.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Characterization of the Faecal Matter, Chicken Manure and Pig Manure

The elemental analysis of Faecal matter, chicken manure and pig manure is presented in Table 4.1.

Table 4:1 Elemental Composition of C, H, N, and S

	Percentage weight (Dry basis)						
Feedstock	**Carbon**	**Hydrogen**	**Sulphur**	**Nitrogen**	**Carbon/Nitrogen**	**Oxygen**	**Ash**
Faecal Matter	43.57±0.54	6.51±0.44	0.43±0.12	5.12±0.00	14.65±0.11	29.4±0.02	14.97±0.01
Pig Manure	28.19±3.06	4.34±0.49	0.26±0.00	2.41±0.15	11.68±0.51	35.89±0.01	28.91±0.03
Chicken Manure	24.52±1.87	3.42±0.23	0.36±0.09	1.68±0.00	8.51±1.21	37.71±0.03	32.31±0.01

The elemental composition of faecal matter, pig manure, and chicken manure directly influences their greenhouse gas (GHG) emissions potential. Faecal matter had the highest carbon (43.57%) and nitrogen (5.12%) content, indicating a higher potential for methane (CH_4) and nitrous oxide (N_2O) emissions. Pig and chicken manures showed lower carbon levels (28.19% and 24.52%) and C/N ratios (11.68% and 8.51%), suggesting a higher risk of ammonia (NH_3) volatilization, particularly from chicken manure. The ash content, highest in chicken manure (32.31%), reflects greater mineral content, which aligns with reduced methane potential but increased risk of nutrient runoff (Huang et al., 2018). These results were used to explain the contribution of each element in the bioconversion process of each three streams by BSF.

4.2 The Concentration of Greenhouse Gases Emitted from Bioconversion Process.

The cumulative concentration of greenhouse gases (CH_4, CO_2, N_2O, and NH_3) was measured over 15 days in parts per million (ppm). The average greenhouse gas concentrations of the substrates, expressed as mean ± standard deviation (SD), are presented in Table 4.2.

Table 4.2: Cumulative Concentration of Greenhouse Gases for 15 Days

Substrate	Cumulative Concentration of Greenhouse Gases for 15 Days (ppm)			
	Methane	Carbon dioxide	Ammonia	Nitrous Oxide
BSF_FM	195.75 ± 3.00	195.38 ± 1.00	0.9712 ± 0.20	0.0953 ± 0.11
FM	2205.32 ±160.00	10210.99 ± 22.00	87.58 ± 58.00	3619.55 ± 100.00
BSF_PM	20.30 ± 1.29	126.14 ± 1.03	1.22 ± 0.69	0.159 ± 0.60
PM	148.58 ± 0.89	1176.20 ± 1.70	53.26 ± 0.34	0.55 ± 0.01
BSF_CM	393.57 ± 1.50	138.22 ± 1.80	19.95 ± 0.59	0.8292 ± 0.01
CM	3544.37 ± 74.00	94853.59 ± 350.00	219 ± 1.50	44294.91 ± 200.00

Among substrates tested in Table 4.1 CM emitted CO_2 94853.59 ± 350 ppm and N_2O 44294.91 ± 200 ppm, FM produced CH_4 2205.32 ±160 ppm and NH_3 8758 ± 58 ppm concentration, while PM emissions were with CO_2 1,176.20 ± 1.7 ppm, followed by NH_3 53.26 ± 0.34 ppm, CH_4 148.58 ± 0.89 ppm, and N_2O 0.55 ppm. In contrast, as shown in Table 4.1 BSF_FM recorded CH_4 195.75 ± 3 ppm, CO_2 195.38 ± 1 ppm, NH_3 0.9712 ± 0.2 ppm and N_2O 0.0953 ± 0.11. BSF_PM emissions of CH_4, CO_2, NH_3 and N_2O were 20.30 ± 1.29 ppm, 126.14 ± 1.03 ppm, 1.22 ± 0.69 ppm and 0.159 ± 0.6 ppm respectively. BSF_CM recorded emissions of CH_4, CO_2, NH_3 and N_2O were 393.57 ± 1.5 ppm, 138.22 ± 1.8 ppm, 19.95 ± 0.59 ppm and 0.8292 ± 0.01 ppm respectively.

The results showed significant variation across all the gases measured. CM had the highest GHG emissions, with the highest levels of CO_2 and N_2O, while FM released the most CH_4 and NH_3. In contrast, PM had the lowest emissions across all gases, with CO_2 being the most emitted and N_2O the least. Similarly, with different substrates, a study by Zeng et al. (2023) showed high cumulative GHG emissions during composting particularly from food waste and chicken manure where CO_2 was 186,127 ppm and 173,900 ppm respectively, highlighting significant emissions of CO_2, CH_4, and N_2O from various substrate tested.

BSF_FM recorded the lowest emissions across all the gases tested. This showed the potential of BSF to reduce the amount of GHG emitted during the bioconversion process. This is confirmed by Lindberg et al. (2022) on composting of fruits and vegetable waste with and without pre-treatment. The study found that CH_4 and N_2O emissions expressed as CO_2-eq, were very low (40 –1,570 ppm) compared with direct CO_2 emissions (47,000–147,000 ppm). A study carried out by

Xiang et al. (2024), showed the same trend as the greenhouse gas emissions CH_4, CO_2, NH_4, and N_2O were reduced by the larval bioreactor by 62%, 87%, and 95% respectively, compared to composting. Similarly, from this study it was observed that BSF treatment significantly reduced the emissions of CH_4, CO_2, NH_3 and N_2O highlighting the effectiveness of BSF in mitigating GHG emissions during waste processing.

4.3 A Comparison of the Gas Emissions from the Bioconversion of the three Substrates

4.3.1 Faecal Matter

The data presented in Figure 4.1 shows the cumulative emissions of CH_4, CO_2, NH_3, and N_2O for both the control and feedstock substrates over the entire treatment period. CH_4 emissions were 195.75 ± 3 ppm for BSFFM and 2205.32 ± 160 ppm for FM. CO_2 emissions were 195.38 ± 1 ppm for BSFFM and 10210.99 ± 229 ppm for FM. NH_3 emissions were 0.9712 ± 0.2 ppm for BSFFM and 87.58 ± 58 ppm for FM. N_2O emissions were 0.0953 ± 0.11 ppm for BSFFM and 3619.55 ± 100 ppm for FM respectively.

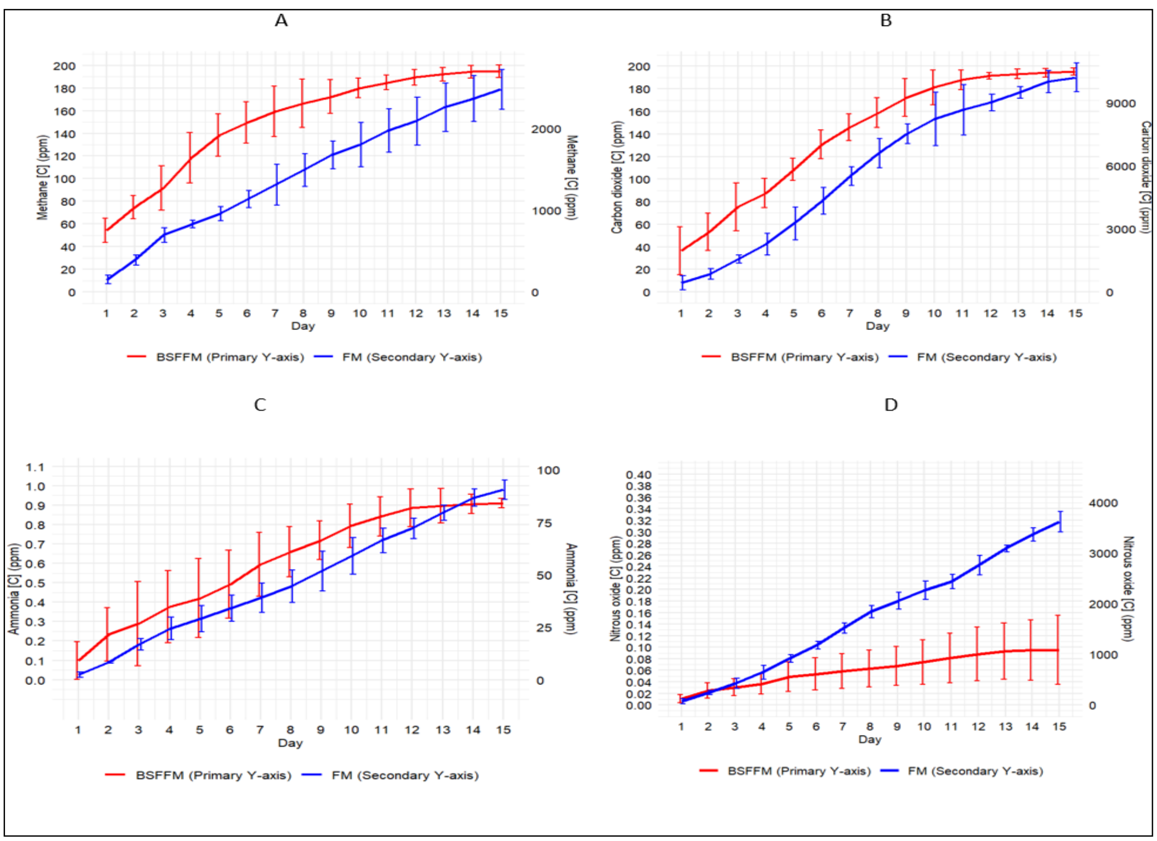

Figure 4.1: Cumulative Data from Faecal Matter with BSF (BSFFM) and without BSF (FM) for Various Gases (A-Methane, B-Carbon dioxide, C-Ammonia, D-Nitrous oxide)

Emission rose steadily during the first 6–7 days with the BSFFM, after which it stabilized toward the end. This was due to initial microbial activity and metabolism of the larvae as the BSF adapted to the substrate. In the initial stages, larvae actively consume easily degradable organic compounds, accelerating the decomposition process and increasing the GHG (Perednia et al., 2017). As the process progressed beyond 7 days the emissions showed a tendency towards stabilization as easily degradable organic matter became depleted, and larval metabolic activity slowed. This stabilization phase characterized by reduced substrate availability and lower emissions rates, corresponds to the findings of Pang et al. (2020). This phase indicates that substrate waste decomposition during bioconversion process had reached a stable state.

On the other hand, the FM for all gases emitted, showed a steady upward trend over time, reflecting the ongoing microbial activity during the decomposition of the untreated faecal matter. GHG emissions increased steadily with relatively higher levels compared to BSF_FM, indicating the dominance of the decomposition process. A similar trend was reported by Matos et al. (2021), on their study that manure storage promotes anaerobic microbial activity, leading to the production of GHG during the decomposition of organic matter.

4.3.2 Pig Manure

The data for the emission levels of the gases measured CH_4, CO_2, NH_3 and N_2O are presented in figure 4.2.

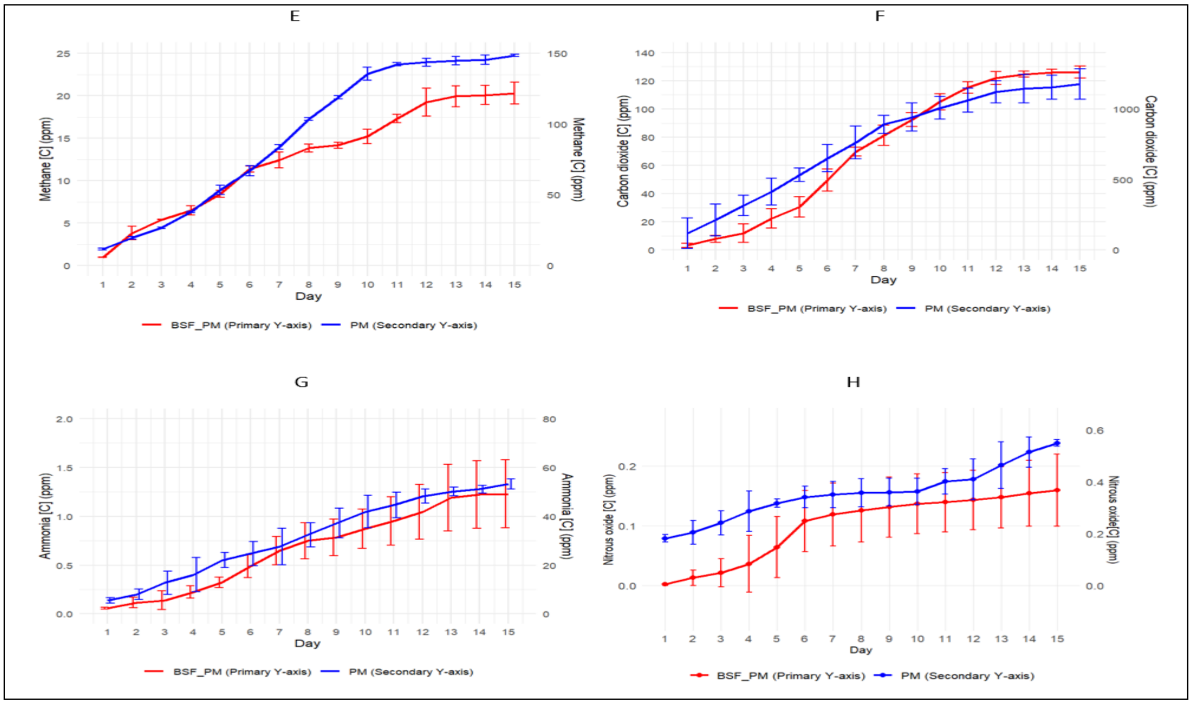

Figure 4.2: Cumulative Data from Pig Manure with BSF (BSF_PM) and without BSF (PM) for Various Gases (E- Methane, F-Carbon dioxide, G-Ammonia, H-Nitrous oxide)

CH_4 emissions were 20.30 ± 1.29 ppm for BSFFM and 148.58 ± 0.89 ppm for FM. CO_2 emissions were 126.14 ± 1.03 ppm for BSFFM and 1176.20 ± 1.7 ppm for FM. NH_3 emissions were 1.22 ± 0.69 ppm for BSFFM and 53.26 ± 0.34 ppm for FM. N_2O emissions were 0.159 ± 0.6 ppm for BSFFM and 0.55 ± 0.01 ppm for FM. The graph showed a comparison of emissions of different gases between PM and the BSFPM. This demonstrated that the bioconversion of pig manure using Black Soldier Fly Larvae (BSFL) significantly reduced GHG emissions compared to pig manure under control. These results aligned with previous studies such as, Chen et al., (2019a), Albalawneh et al. (2024) which revealed the efficiency of BSF in reducing GHGs during bioconversion. In the early days of the experiment, the gases emitted in BSF_PM were generally higher, probably due to the metabolic processes of the larvae that initiate the decomposition of substrate organic matter. PM emissions increased more rapidly, probably due to microbial activity in the absence of larval intervention. Towards the end of the experiment, the BSF_PM line graph on all the gases reached lower plateaus. This is because the BSFL consumed all the organic matter on the PM substrate (Cattaneo et al., 2025).

In General, of the gases measured CO_2 was the most emitted showing a significant increase over time with, 126.14 ± 1.03 ppm for BSF_PM and 1176.20 ± 1.7 ppm for PM. N_2O had the lowest emission levels compared to other gases with 0.159 ± 0.6 ppm for BSF_PM and 0.55 ± 0.01 ppm for PM. These results are in line with previous research that indicated that CO_2 and CH_4 are predominant in manure-based processes due to microbial activities while N_2O is often minimal under anaerobic and semi-aerobic conditions (Parodi et al., 2021). The observed trend has shown the potential of BFSL not only for climate mitigation but also for waste management.

4.3.3 Chicken Manure

Figure 4.3 shows CH_4 emissions as 393.57 ± 1.5 ppm for BSFFM and 3544.37 ± 74 ppm for FM. Similarly, CO_2 emissions were 138.22 ± 1.8 ppm for BSFFM and 94853.59 ± 350 ppm for FM, while NH_3 emissions were 19.95 ± 0.59 ppm for BSFFM and 219 ± 1.5 ppm for FM respectively. Over the same study period, N_2O emissions were 0.8292 ± 0.01 ppm for BSFFM and 44294.91 ± 200 ppm for FM.

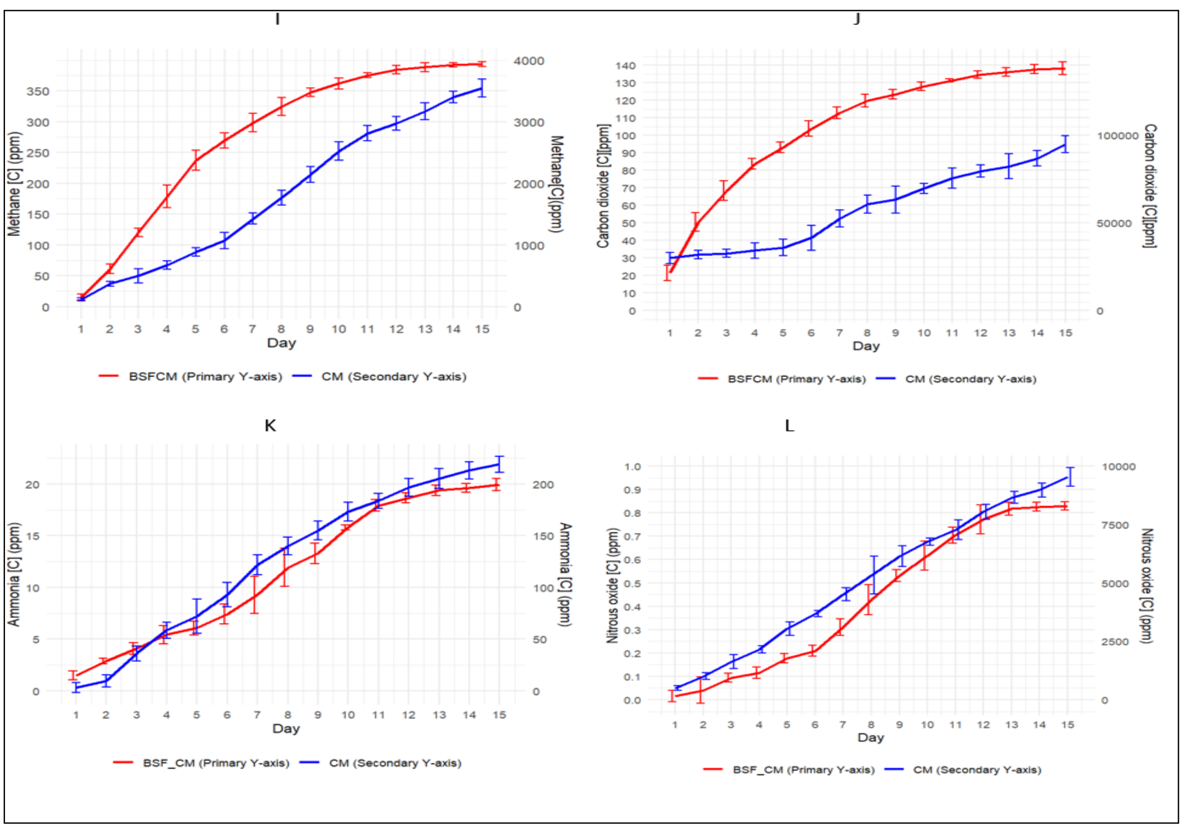

Figure 4.3: Cumulative Data from Chicken Manure with BSF (BSF_CM) and without BSF (CM) for Various Gases (I-Methane, J- Carbon dioxide, K-Ammonia, L-Nitrous oxide)

Chicken manure showed a similar trend to pig manure. For all the gases, CM consistently showed higher emissions than BSF_CM as indicated by the secondary y-axis. Overall, from the results presented graphically, a distinct pattern for each gas was observed, with CO_2 being the most prominently emitted gas throughout the experiment (94853.59 ± 350). This notable CO_2 emission is consistent with a recent study showing that CO_2 is an important byproduct of organic matter during decomposition. It is reported confirmed by Ermolaev et al. (2019b) who found that CO_2 was the most emitted gas during small-scale mass composting of fly larvae with BSF. The average total emission of the gas was 96,000 ppm of processed food waste. However, CO_2 emissions from BSF_CM were lower than CM at 138.22 ± 1.8 ppm. CH_4 emissions were considerably higher in CM at 3544.37 ± 74 ppm, reflecting the anaerobic conditions that favored methanogenesis, but emissions were lower in BSF_CM at 393.57 ± 1.5 ppm. NH_3 emissions increased steadily with CM, resulting in higher cumulative concentrations 219±1.5 ppm, indicating more pronounced nitrogen mineralization. In contrast, BSF_CM produced significantly lower emissions 19.95 ± 0.59 ppm, suggesting a reduction in nitrogen release during the process. N_2O emissions were generally lower on this substrate compared to all gases tested 0.8292 ± 0.01 ppm from BSF_CM. These results showed that BSFL can reduce GHG compared to traditional composting methods.

4.3.4 Methane Emissions from the three Substrates

Cumulative CH_4 concentrations in BSF_FM and FM were measured at 19.75 ± 3 ppm and 2205.32 ± 160 ppm, respectively. Pig manure emission was recorded as 20.30 ± 1.29 ppm for BSF_PM and 148.58 ± 0.89 ppm for PM. While CM recorded 3544.37 ± 74 ppm and BSFCM 393.57 ± 1.5 ppm. Among the control substrates, PM showed the lowest cumulative CH_4 emissions 148.58 ± 0.89 ppm while CM showed the highest emissions 3544.37 ± 74 ppm. Among the BSF-treated substrates, BSF_CM recorded the highest cumulative CH_4 emissions 393.57 ± 1.5 ppm, while BSF_FM had the lowest emissions 19.75 ± 3 ppm as shown in Figure 4.4.

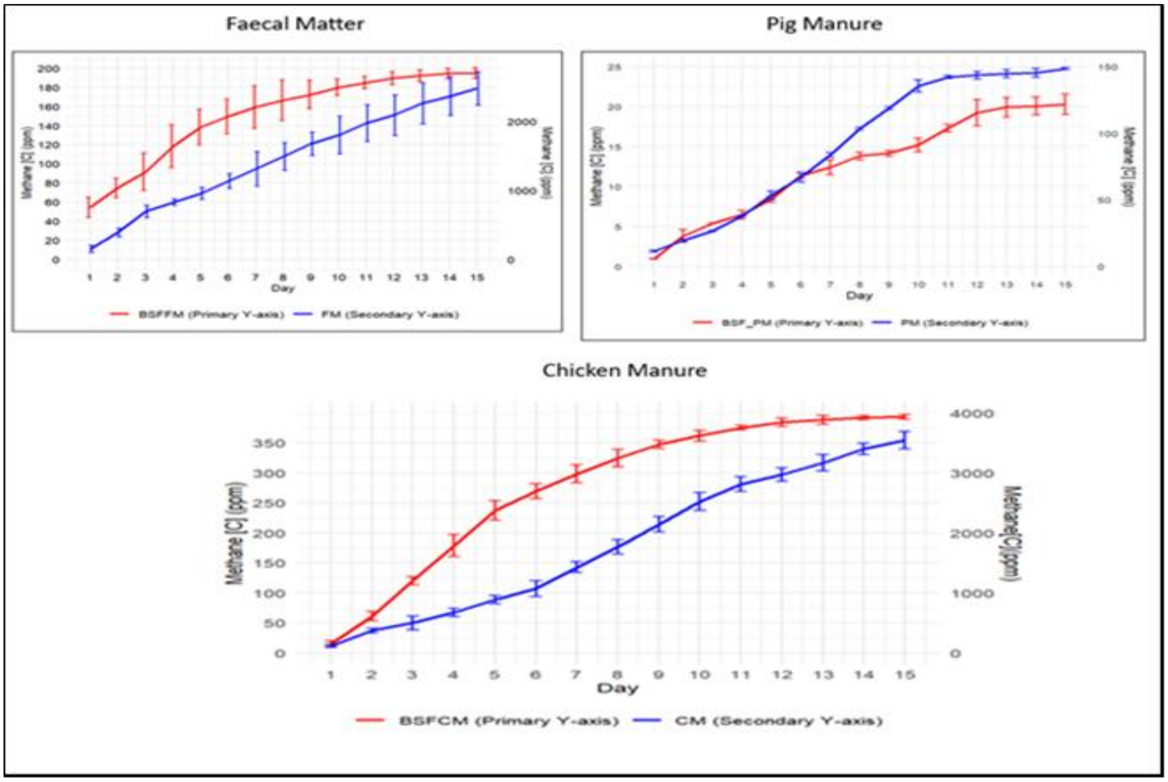

Figure 4.4: Cumulative Gas Concentration for Methane from Faecal Matter, Pig Manure and Chicken Manure with BSF and without BSF

As per IPCC, (2023a), the permissible methane concentration is 1000 ppm. However, chicken manure (CM) exceeded this threshold across all tested substrates, including both the control and the BSF-treated samples. This elevated methane emission occurred despite CM having relatively low total carbon (24.52%) and hydrogen (3.42%) content. The high methane output can be attributed to the high concentration of uric acid in chicken manure, which rapidly decomposes into ammonia under microbial activity. Furthermore, the low C/N ratio 8:51 in CM promotes rapid microbial degradation of organic matter, enhancing anaerobic conditions that support methane production. As a result, the combined effect of uric acid decomposition, high ammonia levels, and a low C/N ratio significantly boosts methane generation in CM, even under BSF treatment.

According to the current study, the feedstock substrate showed significantly lower emissions, while the control substrate showed significantly higher emissions. These showed a reduction in CH_4 emission when using BSFL in all the substrates. A similar trend was reported in a study by Ermolaev et al. (2019b), on GHG emissions from small-scale composting of fly larvae with BSF.

The study also illustrated that direct GHG emissions from the BSFL treatment process were generally minimal, with emissions of CH_4 equivalent to 0.19 ppm per tonne of food waste treated. The results from the current study are consistent with findings reported by previous researchers (Parodi et al., 2021), where gas emissions were high in the first five days and then decreased towards the end. Furthermore, the decrease in CH_4 emissions toward the end of the study could be attributed to increased aeration caused by the movement of larger Black Soldier Fly (BSF) larvae, which introduced more oxygen and reduced the anaerobic conditions necessary for methanogenesis, along with the progressive depletion of the substrate.

In addition, previous research by Matos et al. (2021), on the evaluation of methane emission reduction in pigs revealed that cumulative emissions were 0.00019 ppm suggesting the ability of BSFL to mitigate methane. Methane is a key greenhouse gas due to its high global warming potential, and its presence in the bioconversion process is a point of concern. However, the levels observed in the study were lower than those reported in some traditional waste management methods. This reduction may be attributed to the aerobic conditions promoted by BSFL, which inhibits methanogenesis (Symeon et al., 2025). The results of the current study indicated that BSF has the potential to reduce methane emissions from the bioconversion process, thus offering an alternative to waste management.

4.3.5 Carbon Dioxide Emissions from the three Substrates

The fifteen days cumulative concentration of CO_2 registered and recorded were as follows: BSFFM 195.38 ± 1 ppm, FM 10210.99±229 ppm, BSF_PM 126.14 ppm, PM 1176.20 ± 1.7 ppm, BSFCM 138.22 ± 1.8 ppm, CM 94853.59 ± 350 ppm as shown in Figure 4.5.

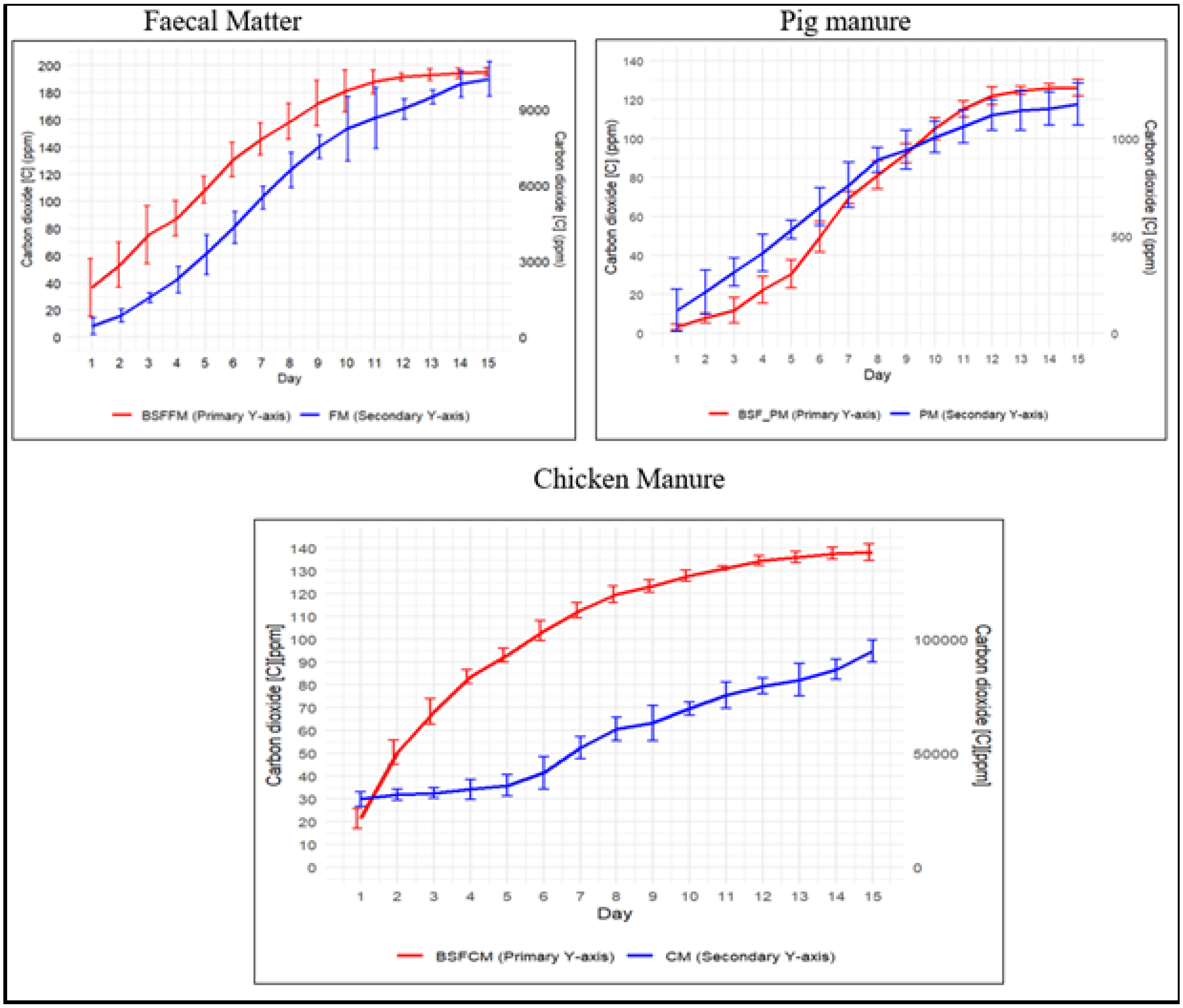

Figure 4.5: Cumulative Gas Concentration for Carbon Dioxide from Faecal Matter, Pig Manure and Chicken Manure with BSF and without BSF

Initially, CO_2 emission was low on both treatments during the first few days. However, emissions increased steadily as microbial activity increased, decomposing organic matter in all substrates. CM had the highest cumulative CO_2 concentration among the control substrates, followed by FM and PM. This is due to its high content of readily degradable organic matter, which is rapidly metabolized by aerobic microbes, leading to intense microbial respiration and elevated CO_2 emissions. Similarly, BSF_CM had the highest concentration among BSF-treated substrates, followed by BSF_FM and BSF_PM. According to IPCC (2023a), the allowable concentration limit of CO_2 is 400 ppm. However, the CO_2 levels recorded in the current study for the substrate treated with BSF were below this standard suggesting that the use of BSF could contribute to better atmospheric CO_2 regulation and potentially offers an eco-friendly solution in reducing the GHG impact.

BSF_FM generated minimal CO_2 compared to extremely high levels from FM. This was further confirmed by a one-way ANOVA, which yielded a p-value of 7.31165E-^{07}, indicating a statistically significant difference between BSF_FM and FM. The results aligned with findings on container-based sanitation in Nairobi, Kenya in a study by Okeny & Niwagaba (2024) where the total emission of CO_2 was 400,000 ppm of faecal matter which was higher than that of BSF_FM**.** Similarly a study by Xiang et al. (2024) reported that BSFL can mitigate GHG emissions by recycling carbon and reconstructing microbial communities that reduced CO_2 emission by 62% compared to non-aeration composting.

The PM showed a clearer and faster increase than the BSF_PM, attributed by the absence of larvae and the unlimited microbial degradation of the organic matter. This trend in the BSF_PM graph was attributed to the higher metabolic activity of the larvae, which resulted in rapid consumption of the organic matter in pig manure. Parodi et al. (2021) found a comparable trend in their study on the evaluation of the reduction of methane emission in swine and bovine manure treated with black soldier fly larvae.

Carbon dioxide emission also followed an upward trend with CM generating higher emissions than BSF_CM. These results showed a significant reduction in this gas which is consistent with recent research findings by Wu et al. (2024), which reported that BSFL bioconversion on chicken manure had a significant carbon loss of 32%. The authors further illustrated that BSFL has a higher conversion efficiency of CM than that of PM. The P-value of 1.19E-^{10} further validated the statistical significance of the results, confirming the robustness of the findings. Another study by Cai et al. (2024), revealed that BSFL is capable of dissolving organic carbon content in chicken manure throughout the process. The results indicated that BSFL contributes to carbon offsetting by reducing carbon loss and lowering emissions through the efficient bioconversion of organic substrates such as CM, FM, and PM manure.

4.3.6 Ammonia Emissions on the three Substrates

In this study, the concentration for BSFFM substrate was 0.9712 ± 0.2 ppm and 87.58 ± 58 ppm for FM. PM recorded a value of 53.26 ± 0.34 ppm while that of BSF_PM was 1.22 ± 0.69 ppm.

CM recorded 219 ± 1.5 ppm and 19.95 ± 0.59 ppm from BSF_CM. This is illustrated in Figure 4.6.

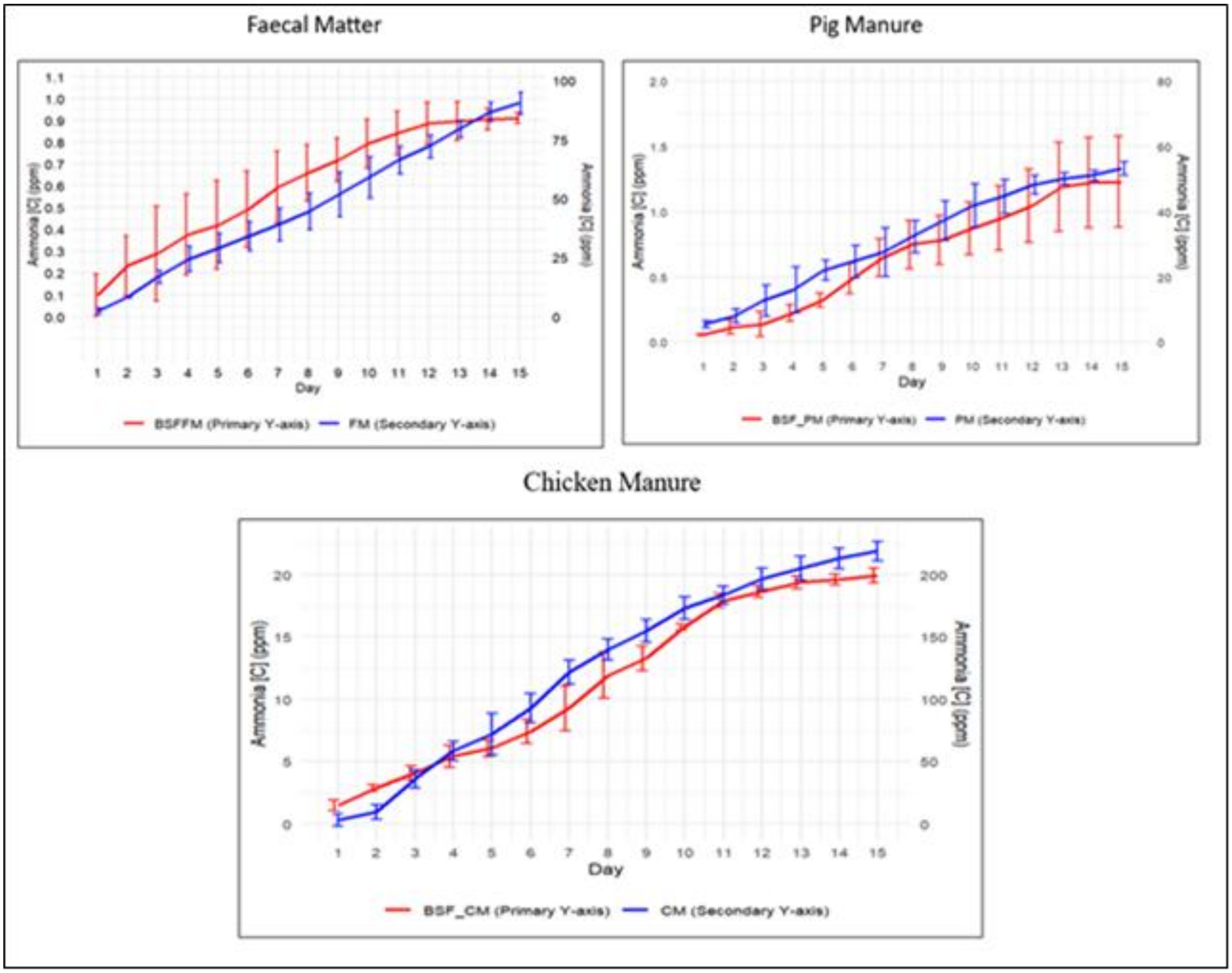

Figure 4.6: Cumulative Gas concentration for Ammonia from Faecal Matter, Pig Manure and Chicken Manure with BSF and without BSF

CM had the highest concentration among the control substrates, followed by FM and PM. In contrast, the BSF-treated substrates showed considerably lower emissions, with BSF_CM recording the highest followed by BSF_PM and BSFFM. According to World Health Organization (2021), the allowable permissible limit for ammonia is 50 ppm. However, ammonia emissions were detected across all three control substrates CM, FM, and PM with concentrations exceeding the allowable limit of 50 ppm. This was attributed due to the decomposition of nitrogen-rich compounds found in the substrates, as revealed by the elemental analysis. Specifically, the relatively high nitrogen content in faecal matter (5.12%) and pig manure (2.41%), and the presence of uric acid in chicken manure, contributed to the release of ammonia during microbial breakdown. However, some of the emitted ammonia was likely re-utilized by microorganisms as a nitrogen source for their growth, which explains why the levels, though elevated, remained lower than CO_2 or CH_4 emissions.

Previous studies have shown that BSF can consume 50% of the manure while digesting 62% of nitrogen element (Rehman et al., 2022). A similar study by Li et al. (2023), revealed that BSFL altered the microbial community structure, enhancing the presence of beneficial microbes while inhibiting ammonifiers which further mitigate ammonia emissions. A study by Becciolini et al. (2023) indicated untreated manure, particularly the mixture of urine and faeces, resulted in significantly higher NH_3 emissions due to microbial decomposition, with emissions being about 100 times higher than from faeces alone under various conditions. Though under various conditions untreated manure exhibited high emissions which was comparable with this study that registered high emissions in FM. The p-value of 5.76831E-^{07} from the study indicated that the difference was statistically significant, confirming that BSFL effectively reduces NH_3 emissions during the bioconversion process.

The results from PM were found to be statistically different with a p-value at 5.70259E-^{08}. The amount of NH_3 released from PM was lower due to larvae's ability to enhance the consumption of nitrogen during bioconversion hence reducing the amount of nitrogen available for conversion into ammonia thereby mitigating ammonia emissions. These results aligned with that of Parodi et al. (2022) on upgrading ammonia nitrogen from manure into protein in BSFL. A study done by (J. Chen et al., 2019b) illustrated that BSF can reduce NH_3 emissions by 82.30%-89.92%. Moreover, CM had the highest emission among all the substrates tested. The p-value of 2.96E-06 between BSF-CM and CM indicated a statistically significant difference, confirming that the inclusion of BSFL in the treatment process significantly reduced ammonia emissions. The lower level of this gas observed in BSFCM was attributed to the larvae's ability to assimilate nitrogen into their body mass, converting it to proteins rather than allowing it to volatilize as ammonia (Lopes et al., 2022).The observed pattern of the BSF treatment in the current study enhanced nitrogen retention by minimizing nitrogen volatilization, which can results to nutrient rich byproducts with higher agronomic value for soil fertility applications.

4.3.7 Nitrous Oxide Emissions on the three Substrates

The N_2O emissions from the tested substrates were as follows: 3619.55 ± 100 ppm from FM, 0.0953 ± 0.11 ppm from BSFFM, 0.55 ± 0.01 ppm from PM, 0.159 ± 0.6 ppm from BSFPM, 44,294.91 ± 200 ppm from CM, and 0.8292 ± 0.01 ppm from BSFCM. This is shown in Figure 4.7.

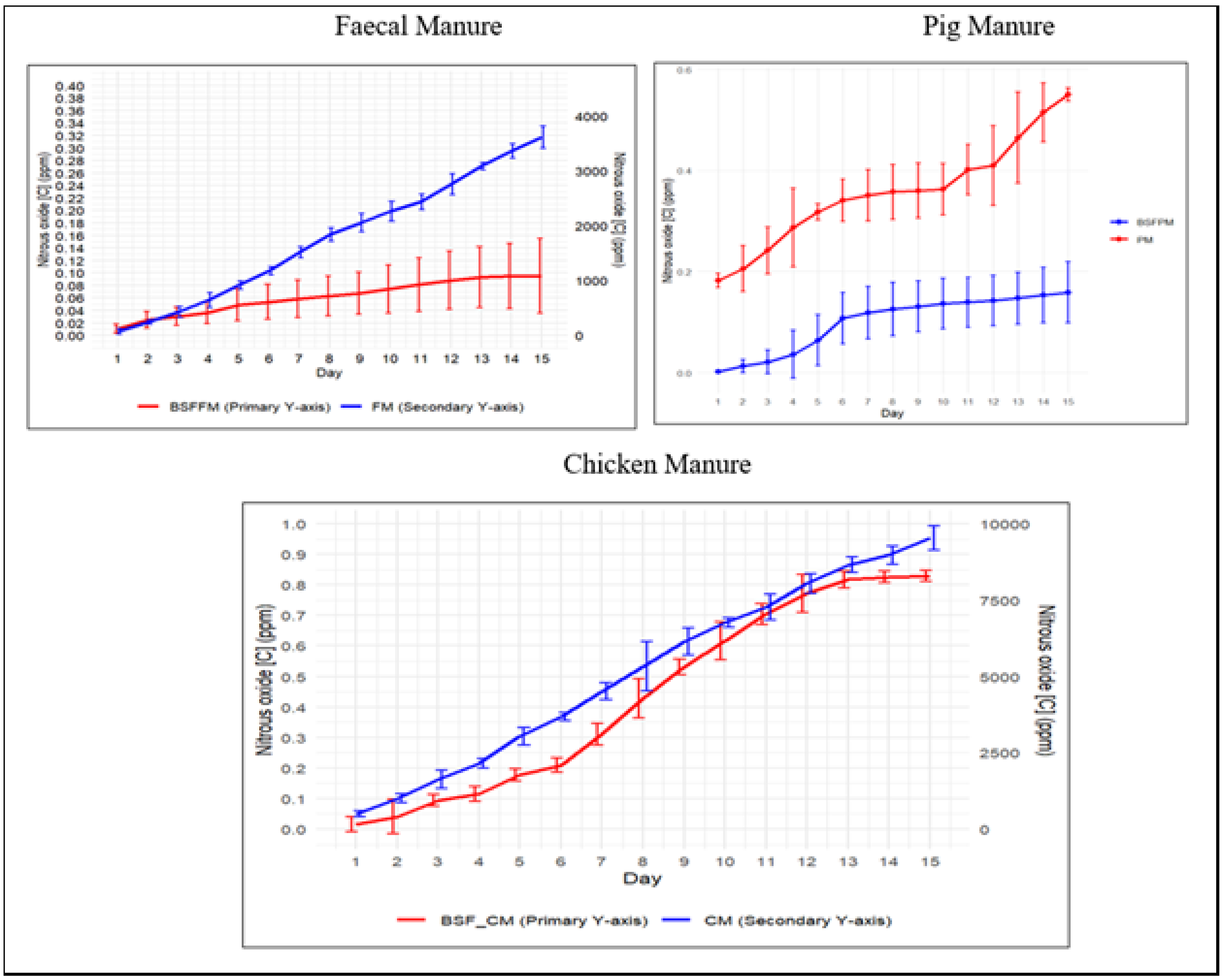

Figure 4.7: Cumulative Gas Concentration for Nitrous Oxide from Faecal Matter, Pig Manure and Chicken Manure with BSF and without BSF

The N_2O emissions varied significantly across the substrates. Among the control substrates, CM recorded the highest emissions followed by FM and then PM. In contrast, the BSF-treated substrates exhibited substantially lower emissions, with BSF_CM recording the highest followed by BSF_FM and BSF_PM. The statistically significant p-values (2.56E-06, 3.84E-09, and 4.11E-07) further confirmed the considerable reduction in N_2O emissions due to BSF treatment across all substrates. According to a study by Gulev et al. (2021) the Intergovernmental Panel on Climate Change (IPCC) established an allowable permissible limit of 100 ppm for N_2O in the atmosphere. The relatively low N_2O emissions can be linked to the elemental composition of the substrates. Although CM had the lowest C/N ratio (8.51), which typically promoted N_2O production, its low nitrogen content (1.68%) limited emissions. FM, with the highest nitrogen content (5.12%), had slightly higher N_2O levels, while overall emissions remained low due to limited available nitrogen. In this study, all tested feedstock substrates exhibited N_2O emissions below this threshold, highlighting the effectiveness of BSFL as a sustainable approach to reducing greenhouse gas (GHG) emissions from organic waste.

Studies have shown similar trends, for instance, Pang et al. (2020) reported that BSFL significantly reduced N_2O emissions compared to conventional organic waste decomposition methods, where emissions are typically much higher due to microbial denitrification processes. Parodi et al. (2021) stated in their research that both N_2O emission were negligible and not significantly different from zero confirming current results. The negligible levels of this gas observed in this study on both treatments showed the minimal environmental impact of this substrate in the process, with BSF_PM offering a slight advantage in further reducing emissions. The preserved nitrogen content in the manure could be used to enhance its value as a biofertilizer. Nitrogen oxide emissions with BSF_CM were the lowest among the gases measured in this study, which is a positive outcome given its extremely high global warming potential. The finding is consistent with other studies that have demonstrated BSFL to reduce N_2O emissions during bioconversion of organic waste. Moreover, a study done by Mertenat et al. (2019), demonstrated that the emission of N_2O from biowaste treatment by BSF was 47 lower than the emission from composting. These results confirmed that using BSFL effectively lowers N_2O emissions, consistent with earlier research highlighting its ability to mitigate greenhouse gas emissions.

4.4 Life Cycle Assessment for Black Soldier Fly Larvae from Bioconversion Process

This study focused specifically on GWP, measured in kg CO_2-equivalent to assess which of the three substrates FM, PM and CM contributed the most GHG emissions during the bioconversion process. The cumulative gas concentration of CH_4, CO_2, N_2O, and NH_3 measured in ppm was converted to mg/kg as per Equation 2.1 (K. & Boguski, 2008) and a summary of the computations is presented in Table 4.2.

Table 4.3: Cumulative Concentration of Greenhouse Gases for 15 Days (kg/kg)

Substrate	**Cumulative Concentration of Greenhouse Gases for 15 Days (kg/kg)**			
	Methane	**Carbon dioxide**	**Ammonia**	**Nitrous oxide**
BSF_FM	0.00019575	0.00019538	9.712E-07	9.53E-08
FM	0.00220532	0.01021099	0.00008758	0.00361955
BSF_PM	0.0000203	0.00012614	0.00000122	0.000000159
PM	0.00014858	0.0011762	0.00005326	0.00000055
BSF_CM	0.00039357	0.00013822	0.00001995	9.53E-08
CM	0.00354437	0.09485359	0.000219	0.04429491

Table 4.4 Illustrates the Inputs and Outputs of this Study

	Inputs					Outputs				
Category	Fuel for Transportation (l)	Substrate (g)	Water (L)	BSF Eggs (g)	Chicken Feeds (Kg)	Frass (g)	CH_4 (kg)	CO_2 (kg)	NH_3 (kg)	N_2O (kg)
FM	3	250	0.4			0.052524	0.00220532	0.01021099	0.00008758	0.00361955
BSFFM	3	250	4	10	2	0.39898	0.00019575	0.00019538	9.71E-07	9.53×10^{-8}
PM	0.5	250	0.4			0.066041	0.00014858	0.0011762	0.00005326	0.00000055
BSFPM	0.5	250	4	10	2	0.064703	0.0000203	0.00012614	0.00000122	1.59×10^{-7}

CM	0.5	250	0.4			0.073103	0.00354437	0.09485359	0.000219	0.04429491
BSF CM	0.5	250	4	10	2	0.064968	0.00039357	0.00013822	0.00001995	9.53×10^{-8}

The analysis estimated the GWP over a 100-year horizon, using the IPCC 2021 guidelines. The comparison provided insight into the potential contribution of these gases towards climate change by each of the waste streams. Notably, CM exhibited the highest CO_2-equivalent emissions, while BSF-treated substrates generally demonstrated reduced emissions. The GHG emissions of the whole treatment system including emissions BSF rearing, transportation, and substrate preparation and emissions from the control substrate and feedstock substrate are presented in Figure 4.8.

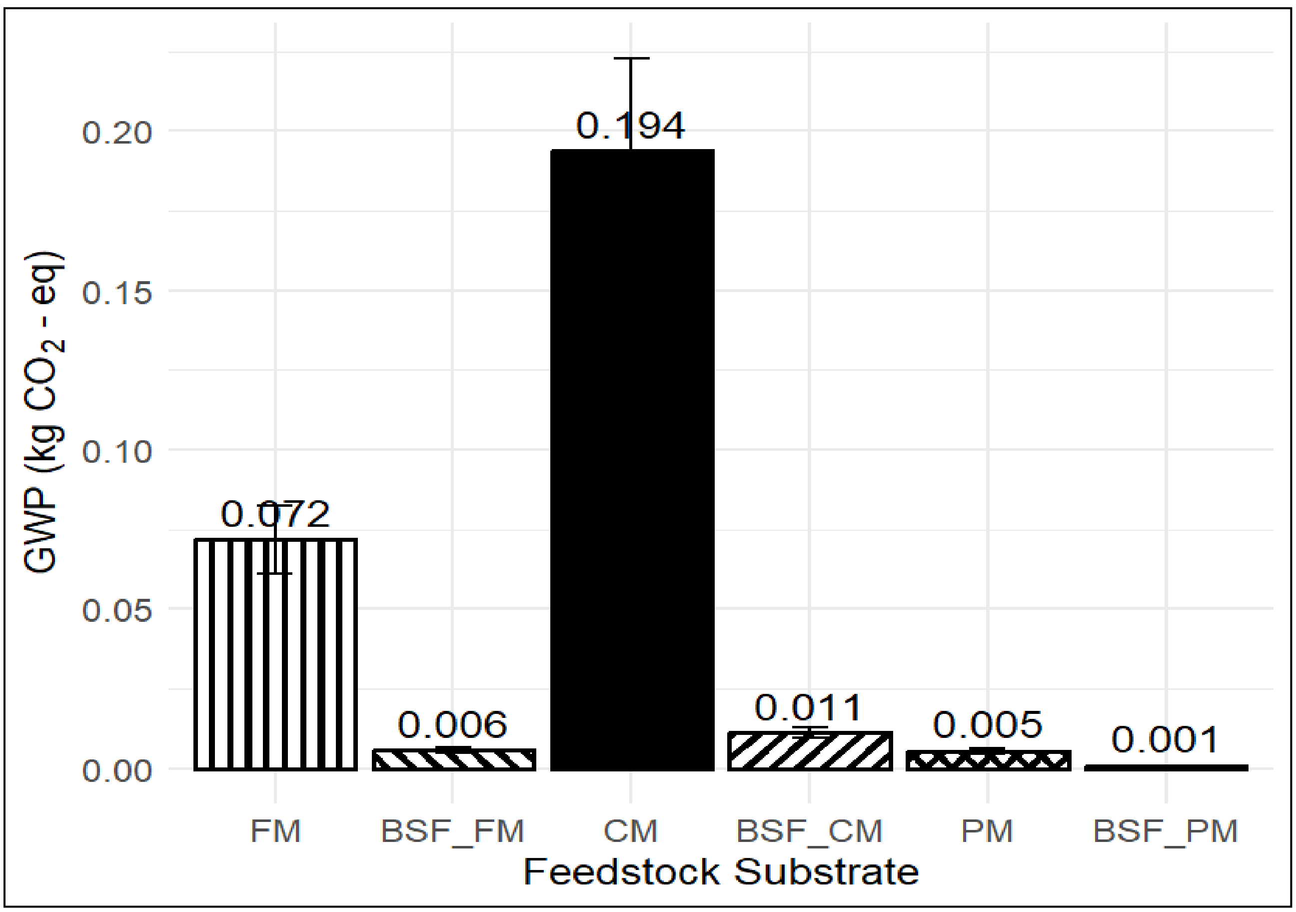

Figure 4.8: Global Warming Potential on FM (Faecal Matter), BSFFM (Faecal Matter with Black soldier fly), CM (Chicken Manure), BSFCM (Chicken Manure with Black soldier fly), PM (Pig Manure) and BSFPM (Pig Manure with Black Soldiers Fly)

The total GWP values were as follows; for CM was 0.194 kg CO_2-eq, for FM was 0.072 kg CO_2-eq, for PM was 0.005 kg CO_2-eq, for BSFCM was 0.011 kg CO_2-eq, for BSFFM was 0.006 kg CO_2-eq and for BSFPM was 0.001kg CO_2-eq. The results of this study demonstrated that BSFL has significant potential to mitigate greenhouse gas emissions, achieving reductions of 94.3% in CM, 91.7% in FM, and 80% in PM.

The substrate with the highest emissions and a correspondingly high GWP cumulatively over the 15 days in the study was CM with emissions of 0.194 kg CO_2-eq. Chicken manure is well known for its high GHG emissions due to its high nitrogen content, which leads to high N_2O and NH_3 emissions during decomposition (Bolu et al., 2018). According to Shakoor et al. (2021), chicken manure management contributed substantially to agricultural GHG emissions due to its rapid nitrogen mineralization and microbial activity. Similarly, Kacprzak et al. (2023), observed that CM, when not properly managed can emit more N_2O than other livestock wastes such as cattle manure due to the higher proportion of uric acid. The high emissions observed here are consistent with these findings, indicating that untreated poultry manure presents serious environmental problems contributing to climate change.

The next substrate with a notable GWP was FM, which exhibited cumulative emissions of 0.072 kg CO_2-eq over a period of 15 days. Faecal matter emissions are largely influenced by anaerobic microbial activity, resulting in high CH_4 and CO_2. A recent study by Lambiasi et al. (2024), reported that untreated human excreta contributed significantly to GHG emission due to the anaerobic decomposition of organic matter, particularly in open or poorly managed sewage systems. Similarly, Shaw et al. (2021) pointed out that decentralized sanitation systems often result in high GHG emissions when not combined with effective management practices. The relatively high GWP observed in this study suggest the need to improve sanitation strategies for mitigating climate change impacts.

Pig manure (PM) recorded a comparatively lower cumulative GWP over the 15 days, with emissions of 0.005 kg CO_2-eq, indicating minimal emissions compared to faecal matter and chicken manure. These results reflect the relatively low PM content which limits N_2O emissions. These results are in line with the results reported by van der Weerden et al. (2021) which evaluated ammonia and nitrous oxide emission factors for excreta deposited by livestock and land-applied manure and reported that pig manure emits significantly less N_2O due to its comparatively lower nitrogen concentrations. In addition, PM tends to have a more balanced carbon-to-nitrogen ratio, which moderates microbial activities during decomposition. When the carbon-to-nitrogen ratio is high it leads to the shortage of nitrogen and the growth of other microorganisms, making the decomposition process long and slow (Zhou, 2016). These results support findings from this study which shown that the GWP associated with pig manure is relatively low.

The substrates acting as feedstock for BSF in this study showed a relatively lower GWP than untreated substrate. BSFFM emissions were reduced from 0.072 kg CO_2-eq to 0.006 kg CO_2-eq, BSFCM from 0.194 kg CO_2-eq to BSFCM 0.011, and BSFPM from 0.005 kg CO_2-eq to BSFPM 0.001kg CO2-eq. These results are in line with findings of several other studies highlighting the potential of BSFL in mitigating GHG emissions through efficient bioconversion processes of the various waste streams. According to Mertenat et al. (2019) on biowaste treatment, the GHG footprint was 47 times lower than that of composting. Another study by Octaviani et al. (2024) found that BSF demonstrated GWP reductions of 1,201.58 kg CO_2-eq and 1,143.4 kg CO_2-eq in food waste mitigation impact analysis. Similarly, the study by Salomone et al. (2017) showed that compared to other traditional composting methods, the global warming potential associated with BSF bioconversion process is minimal. The consistent reduction in GWP for all the substrates in this study supports the integration of BSFL into climate-smart waste management strategies to mitigate the environmental impact of the organic waste streams.

An LCA's impact scores are mostly determined by the part of the system boundary. When all processes and direct emissions are taken into account, as demonstrated by earlier studies, the functional unit typically receives higher results (Boakye-Yiadom et al., 2022). For instance, in a study by Smetana et al. (2019), the authors included the materials and energy associated with other phases, such as the construction of the processing facility, the production of larvae, and additional frass processing to obtain the final dried organic product were able to determine a very high impact score of 877 kg CO_2-equivalent/ton dried organic fertilizer. However, Komakech et al. (2015) reported comparatively low GWP scores of 12.40 and 17.36 kg CO_2 eq./ton FU, respectively, mostly due to the exclusion of several other impacting categories from the system boundary, such as substrate collection, transport, pre-treatment, and larval generation. The current study's emissions differed from those of other researchers because of the distinct functional unit and system boundaries used. The study used a functional unit of 250 grams of each waste stream (CM, FM, and PM). This means that the emissions were calculated based on the treatment of exactly 250 grams of each type of waste ensuring a standardized basis for assessing environmental impact.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following are the conclusions from this study:

i. The results indicated that control substrates produced significantly higher GHGs emissions compared to BSF-treated substrates. FM emitted 2205.32 ±160 ppm CH4, 10210.99 ± 22 ppm CO2, 87.58 ± 58 ppm NH3, and 3619.55 ± 100 ppm N2O, PM emitted 148.58 ± 0.89 ppm CH4, 1176.20 ± 1.7 ppm CO2, 53.26 ± 0.34 ppm NH3 0.55 ± 0.01 ppm N_2O, while CM emitted 3544.37 ± 74 ppm CH_4, 94853.59 ± 350 ppm CO_2, 219 ± 1.50 ppm NH_3 and 44294.91 ± 200 ppm N_2O. In contrast BSFL-treated substrate BSFFM emitted 195.75 ± 30 ppm CH_4, 195.38± 10 ppm CO_2, 0.9712 ± 0.20 ppm NH_3, and 0.0953 ± 0.11ppm N_2O, BSFPM 20.30 ± 1.29 ppm, 126.14 ± 1.03 ppm. 1.22 ± 0.69 ppm, 0.159 ± 0.60 ppm and BSFCM emitted 393.57 ± 1.50 ppm CH_4, 138.22 ± 1.80 ppm CO_2, 19.95 ± 0.59 ppm NH_3 and 0.8292 ± 0.01ppm N_2O thus demonstrating that BSF has a potential to mitigate GHG during bioconversion process.

ii. Among all the substrate tested, CM had the highest GHGs emissions with CO_2 94,853.59 ppm being the most emitted gas, followed by N_2O 44,294.91 ppm, CH_4 3,544.37 ppm, and NH_3 219 ppm. FM recorded the second highest emissions, with CO_2 10,210.99 ppm, followed by N_2O 3,619.55 ppm, CH_4 2,205.32 ppm, and NH_3 87.58 ppm. PM had the lowest emissions among the control substrates, with CO_2 1,176.20 ppm being the highest, followed by NH_3 53.26 ppm, CH_4 148.58 ppm, and nitrous oxide 0.55 ppm.

iii. High emission on CM was reflected on its GWP at 0.194 kg CO_2-eq, followed by those for FM at 0.072 kg CO_2-eq, and minimum for PM at 0.005 kg CO_2-eq. Across all substrates treated with BSF showed a notable reduction in GWP compared to untreated FM 0.072 kg CO_2-eq to 0.006 kg CO_2-eq in BSFFM, CM from 0.194 kg CO_2-eq to BSFCM 0.011, and PM from 0.005 kg CO_2-eq to BSFPM 0.001kg CO_2-eq.

5.2 Recommendations

The following are the recommendations from this study:

i. This study advises further studies can be done to assess how humidity and temperature affect the emission of GHG gases on feacal matter, chicken manure and pig manure.

ii. Further study on comprehensive LCA to compare the environmental impact, GHG emissions and resource recovery efficiency of BSF treatment models against composting waste management systems.

iii. The policymakers should promote the large-scale adoption of BSFL as a climate-smart waste management solution by developing supportive policies and regulatory frameworks. Additionally, the government should provide incentives to enhance awareness campaigns and training programs to educate waste producers, farmers and industries to contribute to the advancement of the circular economy effectively.

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APPENDICES

Appendix 1: Stages of Black Soldier Fly

Figure 1 A: Harvesting Black Soldier Fly Eggs

Figure 1 B: Weighing of Black Soldier Fly Eggs

Figure 1 C: Black Soldier Fly Larvae

Appendix 2

Figure 2 A: Measuring of the Substrate

Figure 2 B: Treatment Unit Setup

Figure 2 C: Monitoring of The Treatment Unit

Figure 2 D: Treatment Unit with Black Soldier Fly Larvae