UNIVERSITY OF CAPE COAST

BIOGAS PRODUCTION FROM INVASIVE AQUATIC WEEDS (WATER HYACINTH AND WATER LETTUCE) FROM THE VOLTA RIVER ESTUARY, ADA-GHANA

FRED KWAKU AHIATI

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BY

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Thesis submitted to the Department of Fisheries and Aquatic Sciences, School of Biological Sciences, College of Agriculture and Natural Sciences, University of Cape Coast, in partial fulfilment of the requirements for the award of a Master of Philosophy (M.Phil.) degree in Oceanography and Limnology

OCTOBER 2021

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere

Candidate's signature………………………………….... Date ………………...

Name: FRED KWAKU AHIATI

Supervisors' Declaration

We hereby declare that the preparation and presentation of this thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

Principal supervisor's signature…………………………… Date ………… ……

Name: PROF. ING. SAMUEL KOFI TULASHIE

Co-supervisor's signature…………………………………. Date ………………

Name: MR. JOSESPH SEFA DEBRAH

ABSTRACT

Water Hyacinth, *E. crassipes*, and Water Lettuce, *Pistia stratiotes* are invasive water weeds that thrive in freshwater bodies and estuaries. These weeds have high cellulose and hemicellulose concentrations, highlighting their potential for generating biogas and other bioenergy sources. Since these invasive aquatic weeds could potentially have a positive economic impact, this study aimed to investigate their possible economic benefits and assess the possibility for biogas production from their biomass. For this investigation, the Volta River Estuary near Ada was chosen as the study area. At Ada, boats were used to harvest weeds from the Volta River Estuary. They were placed in an ice chest and taken to the laboratory. The experiment was performed by first pre-treating the two weeds. The pre-treatment involved using mortar and pestle to pound the weeds to create a larger surface area for microbial activity on the weeds. Pre-treated Water hyacinth/Water lettuce plus cow dung were continually fed into an anaerobic digester for 45days and allowed to generate biogas. Factors such as pH and temperature were closely monitored during the digestion period. The Chemical and elemental composition of the two weeds were also determined. Descriptive and inferential statistics were used to describe the variations in the parameters. At the end of the study, *Eichhornia crassipes* and *Pistia stratiotes* exhibited the potency to be used as feedstocks for biogas production. Based on the Analysis of Variance and Z-Tests findings, it was realized that the means of the biogas yield of the two weeds differ significantly. Consequently, water hyacinth has been identified as the perfect weed suitable for the production of large-scale biogas.

KEY WORDS

Biogas

Invasive Species

Water Lettuce

Water Hyacinth

Renewable Energy

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DEDICATION

To my dad, mum and my nieces; Dela and Elorm.

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LIST OF ACRONYMS

AD	Anaerobic digestion
TS	Total solid
VS	Volatile solid
TAN	Total ammonium nitrogen
TN	Total nitrogen
VFA	Volatile fatty acids
OLR	Organic loading rate
HRT	Hydraulic retention time
RE	Renewable Energy
IUCN	The International Union for Conservation of Nature

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

1.1.1 Historical context

Energy has been an unavoidable worldwide necessity throughout history. It has been described as both a catalyst for growth and a contributor to a slew of global economic and environmental concerns (Gielen *et al.*, 2019). Inadequate and irregular energy sources are one of the three major barriers to Ghana's future economic growth (World Bank, 2020). Historically, the prime source of energy has been fossil fuels, considerably contributing towards global warming and subsequently to climate change. Not only are clean and affordable energy services vital for a sustainable society, but also poverty reduction. International interest in renewable, alternative, and inexpensive energy sources has piqued scientists' interest in biofuels, particularly biogas, as a practicable replacement for fossil fuels (F. M. Brouwer & Van Ittersum, 2010; Anoop Singh *et al*., 2011). The generation of renewable energy can be done through several means, including through the use of biomass.

Organic biomass is obtained from living things such as animals and plants. In terms of energy production, the often-used biomasses are plants, wood, and organic waste. They are collectively called "biomass feedstocks." Through photosynthesis, plants absorb the sun’s energy and convert carbon dioxide and water into nutrients (Bühlmann, 2019). The energy produced by these plants can be transformed directly or indirectly into usable energy in a variety of ways. Biomass can be burned directly to provide heat, converted to power, or processed into biofuel (indirect) (Tun *et al.*, 2019). Biomass is a key source of energy in a lot of developing countries, particularly for cooking and heating. In addition, the use of biomass fuels for transportation and energy generation is expanding in many developed countries (Zhaohua Wang *et al.*, 2020). Biomass is being used so as to minimize carbon dioxide emissions associated with fossil fuel use (Mao *et al.*, 2018). Crops such as sugar cane, corn, soybeans, switchgrass, woody plants, algae, and invasive aquatic weeds are some of the dominant plant biomasses being used. Currently, much attention is being focused on invasive weeds as substrates for bioenergy generation.

The International Union for Conservation of Nature (IUCN) defines invasive alien species as "species that are introduced outside of their natural geographic range, either accidentally or deliberately, and become problematic." Quite a lot of times, they are introduced because of economic globalization and the mobility of people and goods such as shipping, consignments of wood products or the shipment of aesthetically appealing plants to new sites (Dueñas et al., 2021). There are various types of these alien invasive weeds, including water lettuce and water hyacinth, that are particularly problematic.

Water lettuce and water hyacinth are invasive nuisance plants that choke rivers and lakes with masses of floating plant matter in most of the world. They are monocotyledonous perennial aquatic plants found in practically most tropical and fresh subtropical streams. These weeds play a critical role in aquatic ecosystems' structural and functional features; providing refuge and food for fish and aquatic invertebrates, regulating oxygen and nutrient cycles, and accumulating heavy metal pollution from habitats (Prabakaran et al., 2019). When these weeds disintegrate in the absence of oxygen, they produce biogas, a mixture of several gases. An anaerobic bacteria consortium working together to digest organic materials in water hyacinth and water lettuce, produces the biogas (Campanaro *et al.*, 2016; Merlin Christy *et al.*, 2014).

The term "biogas" refers to a number of gases generated during the anaerobic decomposition of organic matter, including methane, carbon dioxide, hydrogen sulphide etc. with methane being the useful combustible fraction in the gas (Ramatsa *et al.*, 2014). This biogas can be utilized to power appliances such as heaters, stoves, and lights. In addition, the digested slurry can be administered as a fertilizer in agricultural fields. Significant methane production as a result of microbial breakdown of organic compounds could be used as a source of alternative energy. The fact that numerous control methods have generally failed to remove water hyacinth and water lettuce from affected water bodies highlight the urgent need for environmentally friendly control methods (Enyew *et al.*, 2020; Hill & Coetzee, 2017; Masilamany *et al.*, 2017; Wang *et al.*, 2018).

Water lettuce and water hyacinth as feedstocks for the generation of biogas have the potential to be a cost-effective technique and an alternative control strategy that is more ecologically friendly and environmentally benign.

1.2 Problem Statement

To date, one of the most serious problems in aquatic systems has been the invasion of water hyacinth and water lettuce, that are difficult to exterminate once established (Julie A. Coetzee & Hill, 2012; Jaklic *et al.*, 2020; Jernelöv, 2017;

Mustafa & Hayder, 2021; Patel, 2012). According to Malik (2007), water hyacinth, *E. crassipes*, and water lettuce, *P. stratiotes*, are invasive aquatic weeds with rapid growth rates that cover enormous water regions in little time. They have wreaked havoc on numerous ecologically and commercially significant waterbodies and productive wetlands as a result of their rapid growth and erratic distribution (Hill & Coetzee, 2017; Patel, 2012; Yigermal *et al.*, 2020). In addition, these weeds contribute to biodiversity loss by providing a microhabitat for disease vectors and pests (Kateregga & Sterner, 2009; Ndimele *et al.*, 2011; Patel, 2012). According to a study by Honlah *et al*., (2019), Ghana's water hyacinth infestation could endanger children's education by obstructing water channels and making it difficult for students to commute by boat.

Since the late 19th century, invasive aquatic weeds have been observed in Africa (CAPPS, 2018; Moran *et al.*, 2013; Nyandoro, 2019). Major infestations in Africa's freshwater bodies began in the early 1950 (Kitunda, 2003). In several water bodies in Ghana, the problem of invasive aquatic weeds has reached nuisance proportions. These include areas at Volta Lake, Lower Volta River, Barekese Reservoir, and Kpong Headpond (Asare, 2015; Nyamekye *et al*., 2021; Osei *et al*., 2021). According to Nyamekye *et al.*, (2021), 'Aquatic weeds occur in the vicinity of Ada and Ada Foah. Pabi *et al*. (2017) stated that of all floating and submerged aquatic plants on the Volta River, water hyacinth has the highest Normalized Difference Vegetation Index (NDVI).

While there are numerous control strategies available, their effectiveness is site-specific and dependent on other factors such as temperature and eutrophication, which limits their application (Hill *et al.*, 2016; Malik, 2007). Chemical, physical, and biological management strategies have already been implemented to combat Ghana's weed invasion but have been unsuccessful in the long run (DeGraft-Johnson & Akpabey, 2005; Akpabey, 2012). Furthermore, the continued failure of current management strategies to completely exterminate these weeds from invading water bodies, as well as their ecological consequences, emphasizes the significance of long-term control measures with associated ecological advantages (Enyew *et al.,* 2020; Hill & Coetzee, 2017; Masilamany *et al.,* 2017; Wang *et al.*, 2018).

Despite being invasive, research shows that these macrophytes have high concentrations of cellulose and hemicellulose, which increases the likelihood that they could serve as a source for biogas and other types of biofuels (Pantawong et al., 2015). It may hence be environmentally sustainable to generate biogas from water lettuce and water hyacinth.

For many years, scientists have been intrigued by the idea of producing biogas from plants like water hyacinth and water lettuce. A sizable amount of biogas has been reported to be produced when these weeds are used as a biomass source for sustainable energy production (Almoustapha et al., 2009; Pantawong et al., 2015; Pottipati et al., 2021). Pottipati et al. (2021) also stated that "biogas yields are increased when a mixture of animal waste and water hyacinth is used, and the sludge produced from the mixed feed contains a higher concentration of nitrogen, phosphorous, and potassium and can be used as very good manure."

Empirical evidence from literature suggest that water Lettuce and water Hyacinth when digested anaerobically, have biogas-producing potential in recent years in Ghana, Niger, Tanzania, Nigeria, India, and China, among other places (Malik, 2007; Njogu *et al.*, 2015; Ofori-Boateng & Kwofie, 2009; Patil *et al.*, 2012, 2014a; Pottipati *et al.*, 2021; Sharma & Suthar, 2021). Kemausuor *et al.* (2015) concluded that biogas could create both skilled and unskilled jobs in communities in Ghana and can also help to displace the use of firewood drastically.

Regardless of the studies done on biogas, the use of invasive weeds for biogas production in Ghana has not been extensively documented. Therefore, this research sought to investigate the potential economic benefits of water hyacinth and water lettuce and assess the feasibility of using them as biomass for the production of renewable energy in Ghana.

1.3 Justification

This study will be critical in light of the current need for an alternative renewable energy that will benefit Ghana and the globe as a whole on social, economic, and environmental levels. When juxtaposed with the extrication and generation of energy from fossil fuels, the Anaerobic Digestion process emits fewer influential greenhouse gases (GHGs) like carbon dioxide and methane to the atmosphere. Cooking and heating are some of the blunt end uses of the produced biogas. Besides, the gas can be refined and used as car fuel and electricity.

Furthermore, the Volta River Estuary at Ada is recognized as one of Ghana's vital water resources and a vibrant economic centre. However, the water body's invasion by invasive weeds causes a slew of issues that jeopardize its socioeconomic development. Although control mechanisms (physical, chemical, and biological have the potential to be effective, they come with a number of drawbacks, including high prices and the detrimental effects of agrochemicals on water quality and non-target living species in the water body when used. As a result, there is a need to identify a long-term, environmentally benign, and cost-effective use for water lettuce and water hyacinth. The utilization of these weeds by anaerobically digesting them to produce biogas will benefit the environment in two ways:

- It would serve as a waste management method that can be used in Cleaning up the Volta River Estuary by the removal/harvesting the weeds through physical means.
- In the agricultural sector, the soil ameliorant property of the digestate (a by-product of the Anaerobic Digestion process) could be rewarding.

Finally, this study will help inform relevant industries and stakeholders on producing Biogas from these invasive weeds in Ghana while decreasing their reliance on the government for subventions.

1.4 Main Objective

To assess the potential of *Eichhornia crassipes* and *Pistia stratiotes* for utilization as renewable energy resources for biogas production from the Volta River Estuary at Ada.

1.4.1 Specific Objectives

1. To analyse the chemical composition of *Eichhornia crassipes and Pistia stratiotes* and their suitability as biogas feedstocks.

2. To evaluate the biogas production potential of water hyacinth and water lettuce from the Ada River estuary.
3. To evaluate the biogas yield from anaerobic digestion and ascertain the cumulative amount of biogas produced.
4. To explore key factors influencing the efficiency of biogas production from water hyacinth and water lettuce.
5. To compare the biogas yields and ascertain the ideal invasive aquatic weed for biogas production in terms of commercialization.

1.5 Hypotheses

1. H_o: Water lettuce and water hyacinth from Volta River Estuary are not suitable feedstocks for biogas production

   H_1: Water hyacinth and water lettuce from Volta River Estuary are suitable feedstocks for biogas production.
2. H_o: There is no difference between the biogas outputs of water hyacinth and water lettuce obtained from Volta River Estuary.

   H_1: There is a difference between the biogas output of water hyacinth and water lettuce obtained from Volta River Estuary.

1.5 Delimitations of the Study

The study was limited to two freshwater/Estuary weeds. Physicochemical parameters in the selected ecosystem were also not captured. Also, only one coastal water body was investigated in the study due to the limited time available for the work.

1.6 Limitations of the Study

The method of transporting water hyacinth and water lettuce is mostly determined by the treatment technique and the scale of the processing operation. The higher the water content of the water hyacinth, the bigger the quantity of the weed that must be carried to the destination. As a result, it is preferable to put the resource processing facility close to the location where the weeds are picked.

1.7 Organization of the Study

The thesis is divided into five chapters. Chapter one summarizes the study's concept, including the background, statement of the problem, justification, aims, and significance. Chapter two includes a survey of the literature pertinent to the topic, covering biogas and its applications, anaerobic digestion, and aquatic weed-related difficulties. Chapter three discusses the study area, materials, procedures, and the statistical techniques utilized to analyse the data. Chapter four offer the results and discussion. Chapter four is broken into two sub-sections; the first section presents the findings, while the second section discusses the findings in details. Chapter five concludes with conclusions and recommendations. Additionally, references and appendices are some other components included in this thesis.

1.8 Chapter Summary

Throughout this chapter, there are seven sections to consider. The first section provided an overview of the study's context, while the second section concentrated on formulating the problem statement. Both the basis for the investigation and the study's aims were discussed in further detail in the third and fourth sections. The fifth and sixth sections of the study were devoted to the study's limitations, and delimitations. The final phase of the investigation was dedicated to the organization of the data. The next chapter will delve in the literature that has been written about this particular research project.

CHAPTER TWO

LITERATURE REVIEW

Introduction

Using the literature on the suitability of water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*) as biogas feedstocks, this chapter examines the pros and cons of each plant. This chapter also discusses a variety of topics, including biogas plants in Ghana, the invasion of water hyacinth and water lettuce in Ghana, among others.

2.1 Water as A Limiting Resource

All living things require water to survive (Newete *et al.*, 2014). In spite of the fact that water covers 75% of the earth's surface, 97.5% of it is salt water, with the remaining mostly locked away as groundwater or in glaciers. Fresh water suitable for human consumption accounts for less than 1% of the total (Backhaus *et al.*, 2019). Aquaculture and industry, as well as ecosystem maintenance, are all dependent on water availability (Matthews & Bernard, 2015). Although the world's population can rely on an annual supply of approximately 9000 cubic kilometres of freshwater, this supply is not evenly distributed throughout the planet.

Ghana is blessed with a plentiful supply of water resources. The Oti, Pra, Tano, Kakum, Ayensu, Ankobra and Volta River are some examples. All of Ghana's rivers travel south to the Gulf of Guinea, where they meet the sea. With a catchment area of approximately 70% of the country, the Volta River, which drains the entire northern, middle, and eastern regions of Ghana, remains the most important river.

The proportion of water accessible, however, varies greatly from season to season and year to year. Hydrologists classify countries as "water-scarce" if their indigenous water supplies are less than 1000 cubic meters per person per year (Hirji & Grey, 1998; Tortajada *et al.*, 2019). Many parts of the world, including Ghana, are experiencing declining water levels. Rivers have receded, lakes have shrunk, and boreholes are being drilled deeper in order to tap into falling water tables. Water scarcity affects approximately 80 countries, accounting for 40 percent of the world's population, in some locations or at certain times of the year. Some island nations, such as Cape Verde and Barbados, are nearing the end of their freshwater supply. This decline is due to rainfall insecurity, increased population growth, environmental degradation, river pollution, and wetlands draining (Oberholster & Ashton, 2008).

Fresh water is treated as if it will never run out, with little or no acknowledgement that it is a limited resource. Water demand will rise in tandem with population growth and rising living standards. Not only must demand be met, but the natural water cycle must also be preserved for future generations of life. As a result, the world must find ways to meet demand while also preserving the natural water cycle.

2.2 Estuaries

Estuaries are transitional environments with a diverse range of habitats. They are defined as the point where fresh water from rivers meets and mixes with salt water from the sea. Estuarine ecosystems are complex assemblages of constantly shifting habitats (Good, 1997; Roland and Kathleen, 2006). The term estuary is difficult to define due to the intricacies of estuarine situations. However, Donald Pritchard defined an estuary as "a semi-enclosed coastal body of water with free access to the open sea and inside which sea water is demonstrably diluted with fresh water created from land drainage" (Pritchard, 1967).

Some of Ghana's estuaries include the Volta River Estuary, Pra Estuary, Ankobra Estuary, and others. These estuaries are critical for the survival of many organisms because they provide habitat for numerous species, function as migratory pathways, and serve as safe havens for threatened and endangered species. They provide excellent resting areas for migrating birds during their migration. Estuaries are significant natural resources that must be managed wisely for the mutual benefit of all who enjoy and rely on them. Estuaries serve as invaluable laboratory for scientists and students, imparting important lessons in biology, geology, chemistry, physics, and social issues.

2.3 Energy Situation Globally and in Ghana

For a long time, energy has been employed to accomplish nearly everything in the world. Population expansion and industrialization are driving more energy usage. Uranium, crude oil, natural gas, coal and oil account for 85% of total primary energy production worldwide (Minde *et al.*, 2013; Mohammed *et al.*, 2017; Ruppert-Winkel & Hauber, 2014; World Bank, 2018). Global warming happens as more GHGs are emitted into the atmosphere. Steps to cut GHG emissions and avert global warming were outlined in the Paris Agreement (COP21) in December 2015. This includes reducing our dependency on energy sources that emit significant levels of GHGs.

Biomass, petroleum, solar energy, and hydropower are Ghana's principal energy sources. The majority of Ghana's energy needs are met by wood fuels such as firewood and charcoal (Armah *et al.*, 2015; Essandoh *et al.*, 2011; Ofori-Boateng & Kwofie, 2009). According to Ghana Energy Commission, (2017), wood fuel accounts for about 70% of Ghana's primary energy requirements. This has grave consequences for deforestation, depletion of carbon sinks and climate change. (Energy Commission, 2020). To reduce reliance on wood and fossil fuels, a cost-effective and sustainable source of renewable energy (RE) must be sought. Technology must be able to deal with energy shortages, deliver pure/clean energy, and lower environmental pollution so as to advance the achievement of the Sustainable Development Goals.

2.4 State of Renewable Energy Globally and in Ghana

Climate change mitigation necessitates the use of renewable energy (RE) alternatives. Renewable energy has the capacity to meet today's rising energy demand, which is being driven by population increase and industrialization. In 2008, renewable energy accounted for 12.9 percent of the world's 492 exajoules (EJ) (2.3 percent hydro and 0.4 percent other sources), with biomass accounting for the majority (2.3 percent hydro and 0.4 percent other sources) (10.2 percent). In third-world countries, 60% of biomass is used for cooking and heating. Government initiatives, declining costs of various renewable energy technologies, changes in fossil fuel pricing, and other factors have all contributed to an increase in renewable energy implementation (IPCC, 2011). Renewable energy is preferred over fossil fuels since it emits less CO_2 into the atmosphere. Ghana's Nationally Determined

Contributions (NDCs) are focused on increasing renewable energy to 10% of total energy mix. Worldwide, a significant number of NDC countries, notably those in Africa, have focused their efforts on increasing the usage of renewable energy sources (Antwi-Agyei *et al.,* 2018; GH-INDC, 2015; Mills-Novoa & Liverman, 2019; The World Bank *et al.,* 2015). By 2030, energy efficiency from existing power plants is expected to triple to 45% due to the fact that Ghana's NDCs on energy is mainly focused on increasing renewable energy which is up to 10% of the energy mix which would boost clean energy for rural regions. (EPA, 2021; GH-INDC, 2015; IEA International Energy Agency, 2019). Because of this, renewable energy is regarded as an important strategy for lowering greenhouse gas emissions.

There are various benefits to using water hyacinth as a biomass source in sustainable energy generation. It, for example, provides an alternative energy source capable of reducing SO_2 and CO_2 emissions into the environment while also assisting in the clean-up of water bodies damaged by the plant (A. Sharma et al., 2016).

2.5 Biogas

Biogas is a sort of long-term gas energy produced by the anaerobic (oxygen-free) decomposition of organic waste (Patil *et al.*, 2012). This requires a complicated process known as anaerobic digestion (AD). Anaerobic treatment is a cost-effective and efficient method of converting organic matter into renewable energy (Mata-Alvarez *et al.*, 1992; Su *et al.,* 2018). According to Igoni *et al.*, (2008), anaerobic degradation can produce biogas naturally in animal guts, underwater, or artificially in enclosed biogas facilities or landfills. In their view, Wellinger *et al.,* (2013), stated that “biogas is produced in plants by the bacterial decomposition of biomass under anaerobic circumstances”. Muzenda (2014), explains that in an oxygen deficient environment, biodegradable organic matter is disintegrated by bacteria for energy and growth through diverse mechanisms into gas and a nutrient-rich digestate. Biogas is made of 30-45 % carbon dioxide (CO_2), 50-75 % methane (CH_4), 1-2% hydrogen sulphide (H_2S), 0-1% nitrogen (N), 0-1 percent hydrogen (H_2), droplets of carbon monoxide (CO), and an iota of oxygen (Akinbami *et al.*, 2001; Farooq *et al.,* 2012; Sefa *et al.*, 2021). The composition of the gas is usually influenced by "the substrates, the fermentation (digestion) process, and the various technical designs of the plant," according to Njogu *et al.*, (2015). This suggests that, as indicated by Ignoni et al. (2008), the percentage constituents of biogas are not fixed but are changed by a range of factors. Regardless of these limits, the principal gases produced by biogas are methane and carbon dioxide.

2.5.1 History of Biogas

Biogas has been around since the tenth century BC, when it was first discovered. More than 3,000 years ago, the Assyrians were the first to use biogas to heat bathwater (Bond & Templeton, 2011; Muzenda, 2014). Modern biogas is sometimes linked to Dr. Jan Baptista van Helmont's 1630 observation of combustible gases bubbling up from rotting vegetable matter. Biogas is available in China, India, and Germany, among other places (Chen *et al.,* 2017). The chemistry of methane was investigated by Berthollet in 1786. His discoveries were bolstered in 1808 when Davey discovered that decaying cattle manure was releasing CH_4 into the environment. It was in 1859 that the world's foremost biogas digester was constructed in a leper colony outside of Mumbai, India, and it was in 1897 that natural gas was used to power a gas engine (Chen *et al.*, 2017). Additionally, in 1896, a waste treatment plant was constructed in Exeter, England to treat the entire city's wastewater, with the biogas recovered being used to power the city's street lamps.

As a result of these initial investigations, the design, implementation, and usage of biogas have grown in scope and sophistication., and by 1925, Essen municipality in England had biogas pumped into residents' houses. In Germany, biogas was first bottled in the 1930s and used to power automobiles as a fuel. Increasing biogas expertise resulted in the discovery of methanogenic bacteria and the environmental parameters required for methane production by Barker and Buswell in the 1930s, which led to increased rigour in the design as well as operation of digesters in the subsequent decades (Abbasi *et al.*, 2012; Muzenda, 2014).

Biogas systems were initially constructed in Ghana in the mid-1980s (Bensah *et al.*, 2010). Biogas technology was chosen as a replacement for traditional cooking fuels and as a means of minimizing deforestation and the environmental concerns that come with it (Arthur *et al.*, 2011a). Many of these biogas facilities however failed soon after they were built due to immature technology and a lack of government assistance.

2.5.2 Composition of Biogas

Table 1: Composition of Biogas as Adapted from Al Seadi et al., (2008)

Substance	Symbol	Amount (% Volume)
Methane	CH_4	50 – 75
Carbon dioxide	CO_2	25 – 45
Water Vapour	H_2O_2	(20°C) – 7 (40°C)
Oxygen	O_2	< 2
Nitrogen	N_2	< 2
Ammonia	NH_3	< 1
Hydrogen	H_2	<1
Hydrogen Sulphide	H_2S	< 1

2.5.3 Biogas Digester

Anaerobic biogas digesters are airtight reactors that use anaerobic digestion to decompose organic waste and transform it into biogas (Silva *et al.*, 2017). Methanogens require an environment that is free of oxygen. Due to this, a biogas reactor must be airtight. To eliminate seepage of water and biogas into the air, it must be both water- and airtight. It also needs to be well-insulated so as to provide a steady temperature for digestion. Also, it must be capable of resisting all fixed and varying stresses and have a modest surface area in order to save building expenses (Abbasi *et al.*, 2012).

A biogas plant is made up of a mixing chamber, an air tight digester with an agitator, a slurry pond, and a gas holder (Bensah *et al.*, 2010). The influent is mixed with water in the mixing chamber before being dumped into the digester, where microorganisms metabolize it. The primary outputs are biogas and digested materials. The latter is kept in a slurry storage tank, while the former is kept in a gas storage tank.

Biogas facilities of various types have been installed around the world. However, because conditions vary widely between areas, each biogas plant must be customized to the specific needs of the location (Ilo *et al.,* 2021)

2.5.4 Classification based on Digester Feeding Mode

Obiukwu & Nwafor, (2016) and Ramatsa *et al.*, (2014) discovered three distinct types of plants as feedstock. The way a digester is fed and how its digestate is removed is one of the most important methods to distinguish one digester from another. Listed below are the different categorization of digesters.

2.5.4.1 Digesters Fed in Batches

Here, the feedstock and digestate are exchanged on a periodic basis. Typically, batch plants have digesters that are charged with fresh substrates and a starter before being left to decompose for a predetermined residence time before being completely removed after the gas has been collected (Al Seadi *et al.*, 2008; Fulford, 2015c; Sasse, 1986). Biogas yield is 50 to 100 percent higher in batch reactors at advanced temperatures and with constant leachate recirculation, hence their operation is similar to landfills (Jungmeier, 2017; Mir *et al.*, 2016; Prasad, 2012). Because the substrate does not have to be supplied through the entry and outflow pipes, lignin and other indigestible debris can be present in batch type of digesters (Fulford, 2015c). Another feature of this category of digesters is their capacity to degrade substrates with high solid content (20 to 40% TS), making it appropriate for use as a dry digester. Third, unlike wet digestion, it does not necessitate churning (Smith *et al.*, 2013; Williamson *et al.*, 2017). Batch digesters may be further classified into three types: single-stage batch systems, sequential batch systems, and hybrid-up flow anaerobic sludge blanket systems (UASB).

This method is suitable for dry fermentation, which results in a cheaper operational cost. However, this is a labour-intensive process due to the feeding and emptying of substrates.

2.5.4.2 Continuous Digesters

Here, charging with feedstock and removal of digestate occur concurrently. It demands homogeneous and fluid substrates. Once the digester has been started, the feedstock is continuously charged (for example, daily) into it (Al Seadi *et al.*, 2008). They have an opening and an outlet continuous-fed digesters have an entrance and an exit point where substrates continuously enter and leave the digester. Configuration of the digester's entrance and outflow is in a way that allow the digestate to overflow into a new pond when a new feed is charged into the digester. In certain cases, the slurry is transported through the digester mechanically, while in others, displacement occurs as a result of the pressure mounted by the newly fed substrate which pushes out the digested material (Fulford, 2015a). In contrast to batch types, the gas output rate is rather consistent and predictable once the digestive process has settled (Obiukwu & Nwafor, 2016). These are the most frequently implemented biogas plants, as they integrate well into the daily operations of a wide variety of organizations and geographical areas. Additionally, it generates stable biogas. The majority of basic digesters, including the fixed-dome, floating and balloon plants are continuous fed. Also, in Ghana, and other parts of the world, continuous fed digesters are the ones currently accessible.

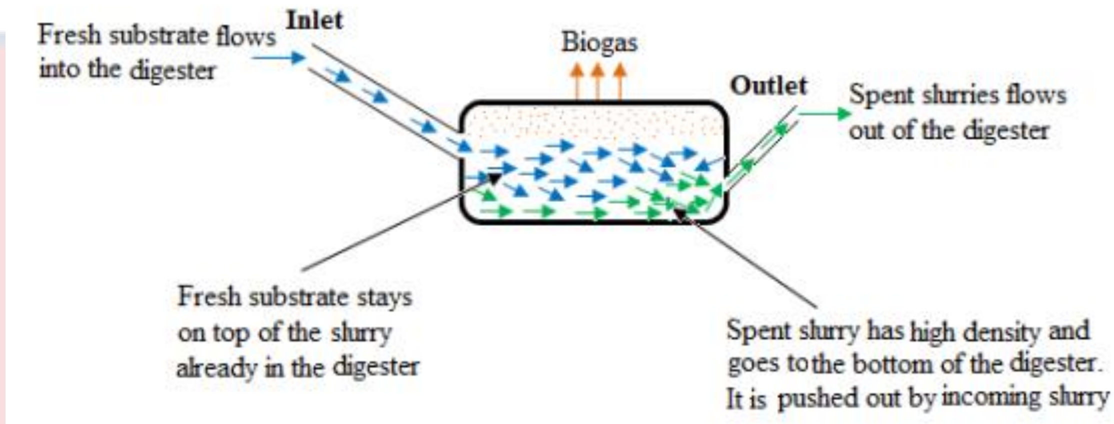


Figure *1:* Schematic representation of how the continuous fed digester works (Ossei-Bremang, 2019)

2.5.4.3 Semi-Batch Digesters

This type of biogas plants begins as batch digesters but are additionally fed on a regular basis. These sorts of plants utilize a variety of substrates with varying degrees of biodegradability. This digester is ideal for co-digesting straw and faeces (Li *et al.*, 2015; Rahman *et al.*, 2017). In China, a lot of digesters are operated in batch mode (Abbasi *et al.*, 2012; Bond & Templeton, 2011; Preston & Rodríguez, 2002; Tagne *et al.*, 2021). Vegetable matter, such as straw and garden waste, as well as animal manure and a starter are added to the digesters. Together with the remaining substrate, the digesters are regularly fed with dung and vegetable wastes. Quick and easy digesting substrates are fed and removed on a regular basis whereas slow digesting substrates are fed twice a year. Due to the rapid decomposition of highly digestible substrates and the boost provided by slower degrading substrates, gas production remains rather constant (Fulford, 2015b).

2.5.5 Classification Based on Construction and Design

Sasse (1986) defined six (6) types of biogas digesters with regards to how they are designed and constructed. Ferrocement, Balloon, Earth-pit, Floating-drum and Horizontal plants are examples of biogas plants. Nonetheless, the mostly employed ones in developing countries are the floating, balloon and fixed-dome plants. The preference for each type of the plant is a number of times influenced by the ubiquitous design in the area, in addition to other factors such as; existing structures, the availability of substrate, space and cost minimization.

2.5.6 Operating a Biogas Plant/Digestion Facility

2.5.6.1 Inoculation or the Initial Phase

The start-up phase of a freshly constructed digester is the most critical (inoculation). Regular operating activities, monitoring, and maintenance are included in the ensuing activities. Anaerobic bacteria are introduced into the digester in this phase. This phase is very essential because the number of microbes present in the digester prior to the introduction of the initial feed determines the effectiveness of the biogas generation process and the duration that will be required for the process to achieve stability (Fulford, 2015b). Anaerobic bacteria can be found in a variety of environments. They can be found in bovine and other ruminant rumen, dung, or droppings. They are also found in marine sediments, marshes, and effluent or slurry from current biogas facilities (Astuti Hidayati et al., 2020; Miah et al., 2005; Abhijeet Singh et al., 2021). They are asserted to be present in some tree species (Oh *et al.*, 2012). Since the digestate is said to contain bacteria, Fulford, (2015a), is of the view that 5% to 30% proportion of effluent from a functioning biogas facility should be combined with the fresh feed. On the other hand, some other researchers advocate for the use of heavy inoculants such as 50:50 inoculum-substrate ratio until the digester is full (Amano *et al.*, 2019; Cao *et al.*, 2020; Sackey D, 2018). During the first few days of operation, the gas given out is of poor quality, has an offensive odour and is non-combustible due to its higher carbon percentage (over 60%) and lesser methane content (Abubakar & Ismail, 2012; Jonsson *et al.*, 2003; Werner *et al.*, 1989). Although some substrates take many days to weeks, to produce quality gas, using cattle dung slurry can generate good gas within two days of start-up (Galletti & Antonetti, 2011).

2.5.6.2 Monitoring and Operational Activities

At the end of a successful start-up phase, the digester's smooth operation can only be maintained by performing certain operational parameters (Habibie *et al., 2021; Sarker et al., 2019; L. Wang et al., 2020)*. In their study, Gopikumar *et al*., (2016), classified the most significant activities into three categories: daily activities, weekly or monthly activities, and yearly activities. Feeding the plant on a daily basis, cleaning the mixing pit, stirring the slurry in the digester on a regular basis, and checking gas pressure are all part of the daily tasks. There must be daily recording of gas output, temperature, and slurry pH. The weekly tasks include monitoring gas appliances, checking for leaks in gas valves, fittings, and appliances, and checking the condition of any installed water traps. Finally, yearly routines involve inspecting and removing scum, inspecting the plant for gas and water tightness, and pressure testing of valves, fittings, and pipelines.

2.5.7 Anaerobic Environment/Digestion

The decomposition of organic compounds by microbes in the absence of oxygen is known as anaerobic digestion (AD). It is a multi-step biological process that mostly converts organic carbon to carbon dioxide and methane (Campanaro *et al.*, 2016). Biogas and digestate are the primary by-products of this process. Biogas is a flammable gas that mostly consists of methane and carbon dioxide, with traces of other gases. Digestate is the decomposed substrate that is produced as a by-product of biogas production. It has been shown that the energy that is chemically bound in the substrate can be retained in the biogas produced in the form of methane to a significant extent (Fagerström *et al.*, 2018). At the opposite end of the spectrum, in aerobic decomposition (which occurs in the presence of oxygen), such as composting, very little heat is produced. The method of producing biogas is mostly grouped into 4 steps;

1. Hydrolysis
2. Acidogenesis
3. Acetogenesis
4. Methanogenesis

However, it must be noted that microbial communities are the primary causes of Anaerobic digestion, and each stage is associated with a distinct collection of bacteria with different dietary and pH necessities (Sharma & Suthar, 2021; Ziganshina *et al.*, 2015; Ike *et al.*, 2010). According to Ziganshina *et al.*, (2014), Fermentative bacteria and fungi have been observed during hydrolysis, acidogenesis, and acetogenesis. Also, the archaeal consortia are responsible for methanogenesis.

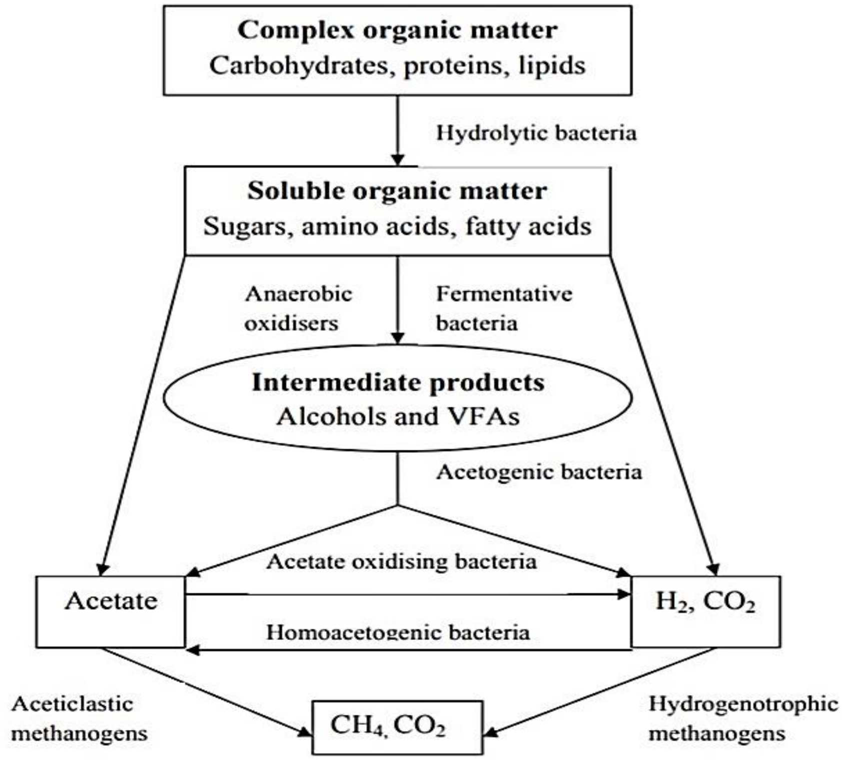


Figure 2: Diagrammatic representation of the anaerobic digestion process

- ***Hydrolysis***

The process of hydrolysis is the first phase and the commencement of the anaerobic digestion process. In the course of the hydrolysis process, extracellular enzymes such as protease, cellulase or lipase hydrolyse composite organic molecules such as proteins, carbohydrates and fatty acids into soluble organic molecules such as amino acids, sugars and fatty acids into soluble organic molecules (Zhang *et al.*, 2014). Proteins, Starch and simple Carbohydrates are easily hydrolysed in the absence of oxygen. With the exception of lignin which is difficult to decompose under anaerobic conditions, other polymeric carbon molecules have a rather slow rate of breakdown. Microorganisms may easily digest cellulose and hemicellulose, two different forms of polysaccharides that are hygroscopic. Cellulose is a polymer made up of a number of glucose molecules, whereas hemicellulose is made up of a variety of sugar molecules (J. Brouwer, 2010; Jørgensen & PlanEnergi, 2009).

- ***Acidogenesis***

Here, the acidogenic bacteria breakdown the biomass and organic compounds that have been hydrolysed. About half of the long chain fatty acids and monomers (amino acids, glucose, xylose) is converted to acetic acid by a balanced bacterial process. For the other half, 30% is degraded to short-chain volatile fatty acids while carbon dioxide and hydrogen gas takes 20% (Jørgensen, 2009; Silva *et al.*, 2017).

- ***Acetogenesis***

The third stage, acetogenesis, produces CO_2, hydrogen gas and acetic acid from acidogenesis. In Acetogenesis, acetate is created from carbon dioxide by anaerobic bacteria using an electron source by means of the reductive acetyl-CoA or Wood-Ljungdahl pathway. The several bacterial species that are capable of acetogenesis are referred to as Acetogens (Abhijeet Singh et al., 2021). In the presence of acetogens, biomass is broken down to the point that methanogens can utilize a significant amount of the leftover material to create methane (Chandra *et al.*, 2012; Menon *et al.*, 2021; Raja & Wazir, 2017).

- ***Methanogenesis***

The last phase in the anaerobic process is carried out by methanogenic bacteria or methanogens. To be able to successfully generate methane, two distinct groups of bacteria are needed. The first assemblage converts acetic acid to methane whereas the second group generates methane from carbon dioxide and hydrogen. Under steady conditions, the breakdown of acetic acid accounts for roughly 70% of methane generation with the outstanding 30% coming from carbon dioxide and hydrogen. The binary processes are precisely balanced and suppressing one would result in inhibiting the other. Of all the bacteria participating in the anaerobic process, methanogens become the limiting factor for how rapidly they process that occur and how much material can be digested due to the fact that they grow at a slow rate (Czatzkowska *et al.*, 2020; Enzmann *et al.*, 2018; Guo *et al.*, 2019). Some examples of these methanogens are methanosarcina, methanobacterium, methanobrevibacter, methanothermobacter and methanosaeta (Campanaro *et al.*, 2016; Sissay *et al.*, 2014).

2.5.7 Factors affecting Anaerobic Digestion and Biogas Production.

2.5.7.1 Temperature

Temperature remains a significant abiotic component in the performance of the anaerobic digestion system since it is one of the key factors determining anaerobic digestion efficiency. In actuality, abrupt environmental changes, such as extreme temperature spikes or reductions, can produce serious perturbations in all process parameters, and the system can take a long time to adapt to a stable condition. Furthermore, temperature has a substantial impact on microorganism development and metabolism, as well as microbial group interactions (Prasad, 2012). There are three different temperature ranges in which anaerobic digestion process can occur. These are, Psychrophilic (below 25^{o}C), Mesophilic (25^{o}C – 45^{o}C), and Thermophilic (45^{o}C – 70^{o}C).

The bulk of methane generated is hinged on the temperature of the digestion. In his words Sasse, (1986) stated that "Low digestion temperatures yield a high methane content but produce less gas". Generally, biogas plants are operated at either a mesophilic temperature of roughly 37°C, where fluctuations of approximately 2°C is tolerated or a thermophilic temperature of 52°C where variations of approximately 0.5°C is allowed (Jacob, 2009).

***2.5.7.2* The Presence of Acidity/Alkalinity (pH)**

The pH value is the measure of the alkalinity or acidity of a solution and it is given in parts per million (ppm). Generally, the growth of methanogenic bacteria is impacted by the pH of the anaerobic digestion substrate. Certain substances like ammonia and organic acids that are essential for anaerobic digestion process are also impacted. Experience has shown that methane generation occurs within a relatively restricted pH range, ranging from around 5.5 to 8.5, with most methanogens preferring a pH range of 7.0-8.0. Acidogenic bacteria often have a lower optimal pH value (Al Seadi *et al.*, 2008). The pH decreases during the first three phases, which are referred to as the acidification phases. During these phases, organic acids like volatile fatty acids emerge (Abbasi *et al.*, 1991; Abbasi *et al.*, 2012).

2.5.7.3 Substrate (Feedstock)

Depending on the starting materials and treatment conditions, the composition of biogas varies significantly. Methane production is minimal if the material is principally made of carbohydrates such as glucose and other simple sugars as well as high-molecular-weight-molecules such as cellulose and hemicellulose. However, when the fat level is high, the creation of methane is also high (Jacob, 2009).

Table 2: Characteristics Of Selected Plants And Selected Products For Biogas Yield (Adapted from Merlin Christy et al., 2014; Merlin & Boileau, 2013).

Base	The dry matter content (%)	The dry matter content of organic (%)	The yield of biogas (m^3/t)	The content of methane CH_4 (% vol.)
Natural fertilizers				
cattle slurry	8-11	75-82	200-500	60
pigs slurry	about 7	75-86	300-700	60-70
cattle manure	about 25	68-76	210-300	60
pigs manure	20-25	75-80	270-450	60
hens manure	about 32	63-80	250-450	60
Plants				
maize silage	20-35	85-95	450-700	50-55
rye	30-35	92-98	550-680	about 55
grass silage	25-50	70-95	550-620	54-55
Products of the agricultural industry				
brewers grains	20-25	70-80	580-750	59-60
grain decoction	6-8	83-88	430-700	58-65
potato decoction	6-7	85-95	400-700	58-65
pomace	25-45	90-95	590-660	65-70
Other substrates for biogas plants				
waste fittings	5-20	80-90	400-600	60-65
gastric contents	12-15	75-86	250-450	60-70
Grasses				
mown grass	about 12	83-92	550-680	55-65

2.5.7.4 Pre-treatment

Pre-treatment is a commercially accessible technique for increasing the solubility and bioavailability of organic materials. This procedure disturbs or alters the refractory structure in an attempt to improve the bioavailability of critical biopolymers. Pre-treatment is required to increase the output of biogas from lignocellulose biomass. Lignocellulosic biomass is made up of a variety of biopolymers that are connected to a variety of linkages to form a stiff assemblage that is resistant to microbial degradation (Jørgensen & PlanEnergi, 2009; Kiran *et al.*, 2016). This rigid structure is made up of three biopolymers: cellulose, hemicellulose, and lignin (Galletti & Antonetti, 2011; Vargas-rechia *et al.*, 2015). A good pre-treatment procedure should have no effect on cellulose or hemicellulose, should not produce enzyme inhibitors, should produce easily digestible cellulosic fibres, and should be economically viable. Physical, physicochemical, and biological pre-treatment procedures are broadly available.

Pre-treatment By Physical Means: Here, the surface area of the substrate on which the enzymes can function is increased. Additionally, it reduces the crystallinity of cellulose. Milling and irradiation are two examples of physical preparation.

Physicochemical Pre-treatments: These are pre-treatment procedures that combine physical and chemical processes. Examples include steam explosions, steam explosions with SO_2 Ammonia fibres, and processing of liquid hot water.

Chemical Pre-treatment: As the name implies, these techniques utilize chemicals such as NaOH, ammonia, and ammonium sulphate (alkali pre-treatment), H_2SO_4, and HCl (acid pre-treatment), H_2O_2, and ozone (oxidizing), and ClO_2, NO_2 (gas pre-treatment.

Biological Pre-treatment: In this pre-treatment process, microbes like white rot fungi are used to breakdown lignin. These microorganisms are capable of breaking down this pretreatment process, microbes like white rot fungi are used to breakdown hemicellulose and lignin but not cellulose (Patinvoh *et al.*, 2017).

However, the effect of pretreatment is dependent on the substrate. Due to the differences in the properties of the substrates, they behave differently when pre-treated (Muzenda, 2014). Thus, the type of pretreatment prior to AD is critical, since some approaches may create chemicals that hinder the function of the critical microbial populations involved in the AD process (Nwokolo *et al.*, 2020).

2.5.7.5 Amount of dry matter/Dry Matter Content

In general, the weight of a certain feed ingredient is dictated by the volume of water in the feed or the amount of dry matter (DM). The term "dry matter" refers to the substance that remains after water is removed, whereas "moisture content" refers to the amount of water contained in the feed item. To enable microorganisms to breakdown the substance, the dry matter percentage must be less than about 50%. However, in a biogas plant, it should be around 8-10% if the biogas is to remain liquid enough to be piped (Jacob *et al.*, 2018; Jørgensen, 2009). In the case of continuous plants, slurries with a 5-10% solid levels are chiefly well suited (Sasse, 1986).

2.5.7.6 Carbon/Nitrogen (C/N) Ratio

One critical factor that is crucial for microorganism growth in the biogas production process as well as process stability is the composition of the substrate. The substrates must meet the microbes' nutritional requirements in terms of energy and different components required for microbial growth (Schnürer & Jarvis, 2010; Seadi *et al.,* 2008). Availability of nutrients such as nitrogen, carbon, potassium and phosphorus help to sustain microbial activity during AD. It must however be noted that, nitrogen and carbon are regarded as the scarcest nutrients. As a result, the carbon-nitrogen ratio is a critical indicator for AD control. The carbon-nitrogen ratio refers to the amount of carbon relative to the amount of nitrogen in a given amount of feedstock that will be utilised in the anaerobic digestion process. When the C:N ratio of an organic substrate is between 1 and 15, fast mineralization and Nitrogen release occurs, making Nitrogen accessible for bacteria growth (Watson *et al.,* 2002). Microbial immobilization occurs when the C:N ratio exceeds 35. A ratio of 20–30 results in a state of equilibrium between mineralization and immobilization. Generally, a ratio of 20:32 has been proven to be necessary for the synthesis of methane devoid of ammonia inhibition (Leung & Wang, 2016; Pottipati *et al.*, 2021; Smith *et al.*, 2013; Velásquez Piñas *et al.*, 2018; Yang *et al.*, 2019; Yen & Brune, 2007; Zeshan *et al.*, 2012). However, ratios of C/N are sometimes significantly lower or greater than this, therefore it is necessary to employ co-digestion to augment the C-N ratio (Wang *et al.*, 2017; Zhang & Chen, 2016).The carbon is utilized to generate energy whereas nitrogen is needed to support microbial development (Deng *et al.*, 2020; Leung & Wang, 2016; Matheri *et al.*, 2018; Riya *et al.*, 2016). When there is a slow growth of the microbial community, low nitrogen levels are said to be responsible. On the other hand, high nitrogen content can be attributed to the fast growth of the population of microorganisms in a digester during AD (Leung & Wang, 2016). However, when a substrate with a high nitrogen content is broken down, higher quantities of ammonia are produced. Ammonia is known to inhibit the process of anaerobic digestion hence steps must be taken to avoid its production (Mutegoa *et al.*, 2020)

Table 3: : Different substrates with their C/N ratio (adapted from Hagos et al., 2017)

Relatively lower C/N value materials		**Relatively higher C/N value materials**	
Substrates/materials	C/N ratio	Substrates/materials	C/N ratio
Cow dung	16–25	Rice straw	51–67
Poultry manure	5–15	Wheat straw	50–150
Pig manure	6–14	Sugar cane bagasse	140–150
Sheep dung	30–33	Corn stalks/straw	50–56
Horse manure	20–25	Oat straw	48–50
Kitchen waste	25–29	Sugar beet/sugar foliage	35–40
Fruits and vegetable waste	7–35	Fallen leaves	50–53
Food waste	3–17	Seaweed	70–79
Peanut shoots/hulls	20–31	Algae	75–100
Waste cereals	16–40	Sawdust	200–500
Grass/grass trimmings	12–16	Potatoes	35–60
alfalfa	12–17		
Slaughterhouse waste	22–37		
Goat manure	10–17		
Mixed food wastes	15–32		

2.5.7.7 The Organic Load

Another critical metric in the AD process is the organic loading rate (OLR). Organic loading become crucial in continuous digesters because feeds are charged continually into them (Rincón *et al.*, 2008). OLR defines how much volatile solids will be put into the digester each day (Ramatsa *et al.*, 2014; Sarker *et al.*, 2019). In their words, Rajendran *et al.*, (2012) defines OLR as "the amount of organic matter injected into the digester per unit volume of the digester".

According to Chen *et al.*, (2008), it is essential to consider the OLR because of community-specific breakdown capacity since microbial communities are the basic drivers of AD. The AD process will become acidic if more biomass is added than the bacteria can breakdown. The productivity of the biogas is directly related to the OLR. A lower OLR would result in lower biogas productivity. Conversely, organic overloading occurs when the OLR is too high. When there is organic overload, organic acid bacteria increase in population. This results in the build-up and synthesis of volatile fatty acids which in turn lowers the pH of the biodigester (Ziganshina *et al.*, 2015). Increasing OLR can result in process instability since VFAs are said to be lethal to methanogens (Rajput & Sheikh, 2019; Zhang *et al.*, 2015).

Furthermore, if there is the need to change the substrate being used, it must be done steadily to allow bacteria to acclimatize to the new environment (Jacob *et al.*, 2020; Jørgensen & PlanEnergi, 2009).

2.5.7.8 Hydraulic Retention Time

In simple terms, hydraulic retention time is the average time spent in a digester by a feedstock. The capacity of microorganisms to breakdown feedstocks is dependent on the retention time (Guven *et al.*, 2017; Wikandari & Taherzadeh, 2019). Active bacteria are also removed when the digestate is removed (washed out). If the HRT is insufficient to support the growth of anaerobic microbes like slow-growing methanogens in a continuous process, hydraulic overloading may occur. Inadequate HRT may in the end cause acidity of the digester due to VFA build-up (Dereli *et al.*, 2014; Rincón *et al.*, 2008; Vaidyanathan *et al.*, 1985). Necessary to also take into cognizance is the fact that, temperature and substrate type affects the average period a substrate spends in the digester to biodegrade and convert to biogas. According to Njogu *et al.*, (2015), depending on the type of substrate used, temperature affects the HRT. In practicality, a thermophilic digestion has over 8 days of HRT, mesophilic digestion has over 20 days and psychrophilic has over 100 days (Njogu *et al.*, 2015). Also, in selecting a hydraulic retention time, substrates are taken into consideration. In comparison to a refractory substrate, a biodegradable substrate/feedstock with low TS may have shorter retention periods.

2.5.8 Uses/Benefits of Biogas

2.5.8.1 Social benefits

Biogas is a smart solution for developing countries like Ghana, where it can help mothers and children live healthier lives since they bear the majority of energy responsibilities in most homes. School attendance for the girl child may be increased through the time saved from harvesting fuelwood (Holm-Nielsen *et al.*, 2009; Minde *et al.*, 2013).

2.5.8.2 Economic Advantages

Return on investment can be generated by using the digestate as fertilizer. Since digestate contains the nutrients phosphorus, potassium and nitrogen, over reliance on artificial fertilizers can be reduced; thereby saving cost. Also, biogas technology can provide employment opportunities for masons, plumbers and carpenters (Arthur *et al.*, 2011b; Minde *et al.*, 2013).

2.5.8.3 Environmental Advantages

Ghana's widespread usage of wood fuel for cooking and heating has had a negative impact on forest and wood resources. A well-made and constructed digester has multiple advantages: "it improves sanitation; it decreases greenhouse gas emissions; it reduces demand for wood and charcoal for cooking, thereby helping to maintain wooded areas and natural vegetation; and it offers high-quality organic fertilizer" (Paolini *et al.*, 2018). Biogas technology has the possibility of addressing environmental issues like acidification, air pollution and eutrophication, disease spread and climate change (Arthur *et al.*, 2011b; Holm-Nielsen *et al.*, 2009; Paolini *et al.*, 2018; Su *et al.*, 2018).

2.5.8.4 Attainment of Sustainable Development Goals (SDGs)

Biogas technology has the possibility of greatly contributing to the attainment of the SDGs (International Energy Agency, 2017; Jungmeier, 2017).

GOAL 2: No Hunger

- By using digestate as fertilizer, nutrient can be recycled into the soil. This will boost food production, end hunger and malnutrition, and help ensure the future viability of agriculture as a whole.

GOAL 3: Maintaining Good Health and Well-Being

- Waste from landfill and organic sewage that contaminate land and water can be used to rather generate biogas using anaerobic digestion which can reduce diseases associated with drinking polluted water bodies.
- Fatigue and headache caused by the stress women go through in gathering fuelwood can be improved by the use of biogas for cooking in homes.

GOAL 6: Clean Water and Sanitation

- Anaerobic Digesters can be placed anywhere, making them a decentralized tool for municipal waste treatment facilities.
- Raw waste water that is disposed into aquatic systems can be recycled for use by employing anaerobic digesters which eliminates greater part of pathogens that are present in the waste.

GOAL 7 Affordable and Clean Energy

- Using biogas, overreliance on fossil fuel can be minimized.
- Electricity can be generated from biogas produced from the anaerobic digestion of locally produced crops and trash.

GOAL 9: Industry, Innovation and Infrastructure

- By providing a waste treatment facility, organic fertilizer and reliable energy and the development of novel environmental methods, biogas plays a role in the promotion of small and medium scale enterprises.

- Biogas can contribute to mitigating unemployment by creating several forms of job through the construction and installation of biogas system and accessories.

GOAL 13: Climate Action

- • Anaerobic Digester reduces CO_2 and CH_4 emissions by using biogas to replace or minimize the use of fossil and wood fuels (which causes deforestation). This is accomplished by extracting methane from decomposing organic waste and utilizing the methane gas instead of fossil or wood fuel. This is a promising way for climate change action and also a wise tactic in combating global warming.
- Using the biogas digestate for farming, methane and nitrous oxide from inorganic fertilizers and livestock manure is reduced.

2.6 Invasive **Weeds as a Resource**

2.6.1 Water Hyacinth (*Eichhornia crassipes*)

Water hyacinth (*Eichhornia crassipes*) is a fast-growing floating aquatic plant that is a member of the pickerelweed family and is native to tropical and subtropical South America. Currently, it is found throughout all tropical lakes, dams, rivers and swamps (Kunatsa *et al.,* 2013). Within a short time, this weed doubles its biomass making it one of the world's most bothersome weeds (Coetzee *et al.*, 2011; Hirji & Grey, 1998). The plant has thick, glossy, spherical and dark green leaves that are connected to spongy petioles with air-filled sacs that allow it to float in water (Patil *et al.,* 2012; Plummer, 2005). Depending on the environmental conditions, the plant's development might range from a few centimetres to a meter (Coetzee *et al.*, 2011). Reproduction is by both sexual and asexual means (Patel, 2012). Sexual reproduction results in seed formation and this seed can germinate within few days or stay dormant for years. On the other hand, asexual reproduction is accomplished through stolen reproduction or budding (Newete *et al.*, 2014). Asexual reproduction allows the plant to triple its population in a week. The nutrient levels in a body of water relates directly with how this plant develops (Lacoul & Freedman, 2006). *EF. crassipes* grows rapidly in eutrophic, nutrient-rich environments. According to Gunnarsson & Petersen, (2007), “The growth rate of the plant is proportional to the nitrogen content of the leaves”. Below 40°C, growth of the plant is limited. However, *E. crassipes* grows best at 25-30°C.

Figure 3: Harvested water hyacinth plant from Volta River Estuary, Ada-Ghana

2.6.2 Water Lettuce (*Pistia stratiotes*)

Water lettuce, *Pistia stratiotes* is a free-floating plant that is stoloniferous. It has sessile leaves arranged in rosettes. Also, it has leaves that are spongy, thick and has a dense mat of white fuzzy short velvety hairs that covers the its lower surface. These hairs prevent the leaf from becoming wet when pushed under water. The leaves are up to 20 cm long and 10 cm wide. Generally, the leaves are spathulate to widely obovate with a rounded to truncate apex and 7-15 conspicuous veins spreading fanwise from the base. The water lettuce leaves are also pale green in colour (Cilliers, 1987; Holm-Nielsen *et al.,* 2009; Wang *et al.,* 2018). Water lettuce flowers are unisexual, lacking a perianth, and have two stamens. The ovary is one-locular, with many ovules, and the style is thin, with the stigma being penicillate in shape. When viewed in the water, the roots can be up to 50 cm long, many, and slender, with many little branches that give them a feathery appearance (Nuamah, 2017; Pantawong *et al.,* 2015; Tanner *et al.,* 1990).

Pistia stratiotes is found in tropical and subtropical locations all over the world and they are the most extensively dispersed hydrophytes (Holm-Nielsen *et al.,* 2009). Although *Pistia* can be found in a wide range of aquatic settings, it appears to prefer rather stagnant water body. In spite of being free floating, it may thrive in moist soil for extended periods of time. This plant's temperature tolerance limitations are 15 degrees Celsius and 35 degrees Celsius. In terms of optimal growth its temperature range is 22 degrees Celsius and 30 degrees Celsius (Cancian *et al*., 2009; Goode *et al*., 2020; Pushkar' *et al.,* 2010). *P. stratiotes* is sensitive to salinity; salt concentrations of 1.66 percent are harmful to the plant (Hadad *et al.*, 2018; Lacoul & Freedman, 2006; Upadhyay & Panda, 2005).

With regard to reproduction, water lettuce undergoes asexual reproduction through vegetative offshoots that are attached to the mother plant by stolon up to 60 centimetres long. They also undergo sexual reproduction by seed production. Vegetative reproduction is the most important in most locations except Africa.

Figure 4: Harvested water lettuce from the Volta River Estuary, Ada-Ghana

2.6.3 Water hyacinth and water lettuce in Ghana

A number of Ghana's aquatic ecosystems have been adversely affected by the water lettuce and water hyacinth invasion. This invasion poses a threat to the proper usage and management of these water bodies(Ayanda *et al*., 2020; Cilliers *et al*., 2009; Patel, 2012). Rigorous research on aquatic flora and harmful weeds began in 1963 through the conception of the Volta Basin Research Project.

In 1984, in Ghana, water hyacinth was discovered at community l0 in the Tema metropolis, where it was preserved as an aesthetic plant (Ameka *et al.*, 1996; de Graft-Johnson, 1993). By 1987, it had contaminated certain drainage system in Tema metropolis in addition to the Odaw River and its tributaries in Accra. Later in 1990, in the western region, it was found in the Abby-Ehy-Tano River and lagoon complex. Again, in 1998, in the Oti River Arm of Lake Volta, this weed was discovered. By the year 2003, it had reached the Kpong Headpond. Urban areas such as Akosombo, Sekondi-Takoradi, and Kumasi were not left out of this water hyacinth infestation. These two invasive aquatic weeds have been identified as a problem in the Volta Lake, the Lower Volta River, Barekese Reservoir and Weija Reservoir (Ameka *et al.,* 1996; Ameka *et al.,* 2010; Gaudet, 1979; Hall & Okali, 1974; Lawson, 1970). A great deal of anxiety is expressed about what would happen to Ghanaian water bodies if these water weeds are allowed to invade and proliferate.

_2.6.4_ Problems Related to Water hyacinth and water lettuce Invasions

Of all the listed invasive weeds, water hyacinth and water lettuce have been identified as the most dangerous and harmful (Cilliers, 1991; Cilliers *et al.,* 2009). The rapid rate of proliferation has become a major danger to socioeconomic growth (Cilliers *et al.,* 2009). Water hyacinth and water lettuce have a wide range of negative consequences which include social, economic, environmental, and other consequences.

2.6.4.1 Social Impact

E. crassipes may degrade water quality in a variety of ways, as well as attract mosquitoes, snails, and other organisms linked to vector-borne human ailments such as malaria, schistosomiasis, encephalitis, filariasis, and cholera (Gopal, 1987). According to Harley et al. (1996), individuals in Papua New Guinea have perished as a result of a combination of poor nutrition, polluted water, increased disease vectors, and overall poor health, all of which are directly tied to the degrading influence of water hyacinth on the ecosystem. Dense mats make boating difficult for fishermen and may prevent them from fishing completely, denying the residents their major source of protein and occasionally forcing people to relocate. Fields have been abandoned in extreme cases of conflict between *E. crassipes* and rice harvests. The main negative social impacts highlighted by interviewees in the Lake Victoria Basin were an increase in specific diseases, issues related with clean water availability, and community relocation (Mailu, 2001).

2.6.4.2 Economic Effect

These weeds quickly produce dense mats that can fully cover the water's surface. As a result, such dense *P. stratiotes* and *E. Crassipes* stands may have major detrimental consequences for the several human uses of waterbodies. These negative consequences include impeding navigation, fishing, irrigation and transfer of drainage water. They also create situations favourable to the transmission of water-borne infections. Also, they interfere with hydroelectric projects from manmade lakes (Jungmeier, 2017; Segbefia *et al.*, 2019; J. Wang *et al.*, 2018). Nang'alelwa, (2008), also summarizes the economic implications in Zambia's Victoria Falls World Heritage Site. In his summary he noted that water hyacinth invasion has substantial ramifications for hydroelectric power generation, tourism development, native biodiversity, fisheries, and human health. Additionally, decreasing water quality and quantity for domestic use, restricted passage of waterways, and a threat to essential infrastructure are all reported consequences.

Another economic effect is the cost of controlling these weeds. In Malaysia for example, cost of controlling water hyacinth has been estimated at M$ 10 million per year (Dilipkumar *et al.*, 2020).

Also, in Malawi, fishermen have reported reduced catches of fish due to another relatively new infestation in the Shire River (Kaunda, 2013; Liabunya, 2007; Mzuza *et al*., 2015).

2.6.4.3 Environmental Impact

When these invasive weeds proliferate in a body of water, it dramatically affects the ecology, typically resulting in the abasement of the environment and a decrease in biodiversity. According to some researchers, the expansion of invasive weeds has diminished or eradicated natural vegetation in numerous water bodies and wetland areas (Davies *et al*., 2020; Dersseh *et al*., 2019; Dueñas *et al*., 2021). Some native insects, fish, birds, and plants may be harmed by the plants. In Madagascar, for example, large portions of the Alaotra Lake, a biologically important site, have been described to be engulfed with mats of E. crassipes, which are harmful to a variety of species (Rakotoarisoa *et al*., 2015; Rakotoarisoa *et al*., 2016).

The risk of flooding is increased through the blockage caused by these weeds in the pathway of irrigation and drainage channels as well as rivers. According to Gopal (1987), “water flow in irrigation channels is reduced by 40-95%, resulting in flooding in Malaysia and Guyana”.

Among the additional environmental consequences are:

Overwhelming evapotranspiration which results in the loss of water that could otherwise be utilized for agricultural purposes as well as drinking and fishing purposes (Finlayson *et al*., 2005; Jury & Vaux, 2007; Sasaqi *et al.*, 2019; World Water Council, 2000). According to Sasaqi *et al.* (2019), several problems have been triggered in the Batujai Resevoir due to the excessive proliferation of water hyacinth. With a coverage area of more than 20 percent, water hyacinth can cause water loss through evapotranspiration of about 8,000 m^3/day. Benton *et al.*, (1978) also states that a fully developed water hyacinth plant will lose approximately three times as much water through evapotranspiration than as is lost from evaporation of an equivalent area of open water. Again, in a study by Timmer &.Weldon, (1966), it was reported that water loss through evapotranspiration was 3.7 times that from open water.

Furthermore, as soon as carpets degrade, dissolved oxygen concentrations fall and sedimentation rises. Mironga et al. (2012). described the impact *E. crassipes* have on the physicochemical parameters of water in Lake Naivasha, Kenya and noted that infested areas have lower pH levels, higher quantities of free carbon dioxide, lower levels of dissolved oxygen than open water.

***2.6.5* Control methods for Water hyacinth and water lettuce**

Some control measures available for the management of the proliferation of these plants are; Use of biological agents such as weevils, use of herbicides or by harvesting the plant mechanically. The cost efficiency of the control techniques will be determined by the losses caused by weed infestation. Control methods should therefore be incorporated into a long-term maintenance plan. This will be linked to the waterbody's economic importance as well as the indirect effect on the health of the surrounding population via water-borne diseases (Coetzee *et al*., 2011; Sharma *et al*., 2016). These strategies are discussed further below.

- **Physical/Mechanical Harvesting**

Mostly, in countries around the world, the first step taken in mitigating the invasion of these weeds is the use of physical means. Here, the plants can be removed either manually or mechanically (Cilliers *et al.*, 2009). Based on the type and size of the waterbody that is contaminated, various devices can be utilized. Special floating harvesters could be employed in lakes and rivers to collect the debris and dump it on the coast. Again, mowing launches and mowing buckets that are coupled to a hydraulic excavator could be used.

Although this is regarded as a more environmentally favourable strategy, it must be noted that re-colonization of the weeds can occur using this method. Also, this approach is viewed as a temporary control measure (Malik, 2007). Some other disadvantages of using this method are that it is time-consuming, expensive and labour difficult making it unsustainable as a short-term control approach (Deivasigamani, 2013).

Chemical Control

The second method of control is through the application of chemical herbicides. Some countries including Ghana have all used chemical pesticides to combat water hyacinth infestation. Chemicals like 2,4-D, glyphosate, paraquat, and diquat have been used extensively to suppress *E. crassipes* and *S. stratiotes* (Findlay and Jones, 1996; Sharma *et al.*, 2016).

Plants of any age will die and sink when these chemicals are applied at high humid and temperature conditions.

Some disadvantages of using this method are that, usually, re-treatment is required after a few months due to seedling regrowth, re-invasion from outside the sprayed area or re-infestation by plants that were not entirely sprayed. Using chemicals as a control measure has garnered greater attention than the use of physical means. This is because of the reduced time necessary to apply chemical control systems (Kathiresan & Deivasigamani, 2015). However, the usage of chemical herbicides carries a hefty price tag. Additionally, the chemicals impair the water's quality and impede the growth of other aquatic animals in addition to regulating the target plant. Herbicides, in particular, can have a long-lasting environmental impact.

- **Control through Biological Means**

Here, natural enemies such as insects, are employed to kill or reduce the population of these weeds to levels that do not cause economic harm (Vásquez *et al.*, 2015). Over the years, researchers have created and successfully distributed arthropods and fungi as biological control agents against these weeds. Some of the arthropods include *Eccritotarsus catariensis*, *Orthogalumna terebrantis*, *Xubida infusellus*, *Neochetina bruchi*, etc (Dutta & Ray, 2017; Quimby *et al.*, 2021). Furthermore, *Cercospora Pairopi, Acremonium zonatum, Rhizoctonia solani* etc. are considered as suitable bioherbicides for the control of these weeds (Barreto *et* *al.*, 2000; Chandramohan & Charudattan, 2001; Dutta & Ray, 2017; Yigermal *et al.*, 2020). Throughout Africa, there has been an establishment of an internal consortium to aid in producing a mycoherbicide using fungal isolates discovered in the continent for weed management. Also, studies have be conducted to produce *Alternaria eichhorniae* as a mycoherbicide (Bateman, 2001; El-Morsy *et al.*, 2006)

The merit of using the biological measure is that, it is the only long-term means of regulating the proliferation of the plant (Cilliers *et al.*, 2009). Also, due to the high expense of physical and chemical management of waterweed, the biological control strategy has been used.

However, after a period of 3-5 years, the effectiveness of the biological control method is reduced. This is so due to the fact that insects are used, and their population must be increased to the point where they significantly reduce the plant population (Kathiresan & Deivasigamani, 2015).

2.6.6 Failure of Control Methods

Water hyacinth and water lettuce remain the most problematic invasive weeds in countries addressing this situation globally, despite various control measures (Heard & Winterton, 2000; Hill *et al.*, 2012). The size of the aquatic system, temperature and trophic condition are some of the factors that hamper control measures; thus, control strategy performance may be site specific (Cilliers *et al.*, 2009; Hill & Olckers, 2000; Malik, 2007; Moran, 2006). According to (Coetzee & Hill, 2012), the success of water hyacinth biological control will be limited if there is a high nutrient concentration in water bodies since the weeds can withstand and recover quickly from insect attacks.

In Ghana, eutrophication is an issue, and the presence of water hyacinth worsens the situation. Water is extremely valuable, and it is critical that water quality degradation be avoided or managed in order to maintain water conservation (Newete *et al.,* 2014). It is important therefore to adopt sustainable uses of the water hyacinth biomass.

2.6.7 Benefits of water hyacinth and water lettuce to the environment

In spite of the difficulties they cause and their status as invasive plants in most countries, research has shown that the plants' qualities have the ability to become a significant resource in the future (Malik, 2007).

Firstly, they can be employed in agriculture and waste water treatment, (Gunnarsson & Petersen, 2007). They also have large potential for removing a wide range of pollutants from waste water (Prasad, 2012). They are suitable for water filtration and pollution management.

These weeds have phytoremediation ability. Phytoremediation is the process of using plants to extract nutrients from contaminated wastewater (Saha *et al.*, 2017). Water hyacinth plants were shown to be capable of removing nutrients from contaminated bodies of water (Gunnarsson & Petersen, 2007; Gupta *et al.*, 2016; Rezania *et al.,* 2015; Soeprijanto *et al.*, 2020a). In its natural habitat, the weeds floats on the top of the water, while its roots are buried deep within the water, where they are exposed to nutrients (Okoye *et al.*, 2002; Patil *et al.,* 2014; Sanni & Adesina, 2012; Wang & Calderon, 2012; Yan *et al.*, 2017). The weeds use the minerals for growth while simultaneously reducing the concentration of the minerals in the water. *Eichhornia crassipes* has a high potential for heavy metal uptake, including Cd, Cr, Ni, Co, Pb, and Hg (Gyampo *et al.*, 2012; Jungmeier, 2017; Patel, 2012).

Furthermore, different end products such as biogas, alcohol, and bio-fertilizer can be obtained by anaerobically digesting these weeds.

***2.6.8* Water Lettuce and Water Hyacinth as Feedstocks for Biogas Production**

The prospect of transforming water lettuce and water hyacinth has for several years piqued scientist attention. Numerous researches have proven that these weeds can be converted into usable biogas (Almoustapha *et al.*, 2009; Kumar *et al.*, 2008; Kunatsa *et al.*, 2013; Njogu *et al.*, 2015; Ofoefule *et al.*, 2009; Patil *et al.*, 2014; Singhal & Rai, 2003; Wang & Calderon, 2012). At the moment, the focus is on developing cost-effective pretreatment procedures that improve hydrolysis and biogas yield (Ofoefule *et al.*, 2009). All of the research listed above demonstrate that these weeds have the ability to act as feedstocks for biogas generation. In all these studies, various yields of biogas have been observed depending on the pretreatment procedure used. To maximize biogas generation from these weeds, little pretreatment is required. This is critical because basic physical pretreatment methods such as chopping and grinding, as well as biological pretreatment methods such as the utilization of naturally occurring aerobic microbes, can help reduce pretreatment costs while still producing a significant amount of biogas. From literature, pre-treated water lettuce or water hyacinth co-digested with other feedstocks such as cow dung is a promising optimization approach.

In summary, using these invasive weeds as substrates for biogas generation may alleviate some of the problems caused by these weeds. Water hyacinth and water lettuce are renewable, and due to their high proliferation rate, they can serve as a sustainable and ecologically benign source of energy that would reduce the pressure on the national grid as it will aid in cooking and powering generators in towns and villages (Sharma *et al.*, 2016).

CHAPTER THREE

MATERIALS AND METHOD

Introduction

This chapter contains information about the study area as well as the approach employed to attain the study's goal. The first portion provides a well-written profile of Ada Foah, placing emphasis on the estuary as it served as the foundation for the selection of study site. The second segment examines data collection methods and data analysis.

3.1.1 Extent of Study Area and Selection of Sampling Sites

This research was confined to a section of the estuary spanning from the exact spot where the river meets the sea to ten kilometres upstream. It encompasses all of the river's island villages, including Kpetsupanya, Alorkpem, Afrive, Azizakpe, and Adzim and many more.

The choice of the sampling locations was based on the impact and the presence of water lettuce and water hyacinth.

3.1.2 Description of the Study Area

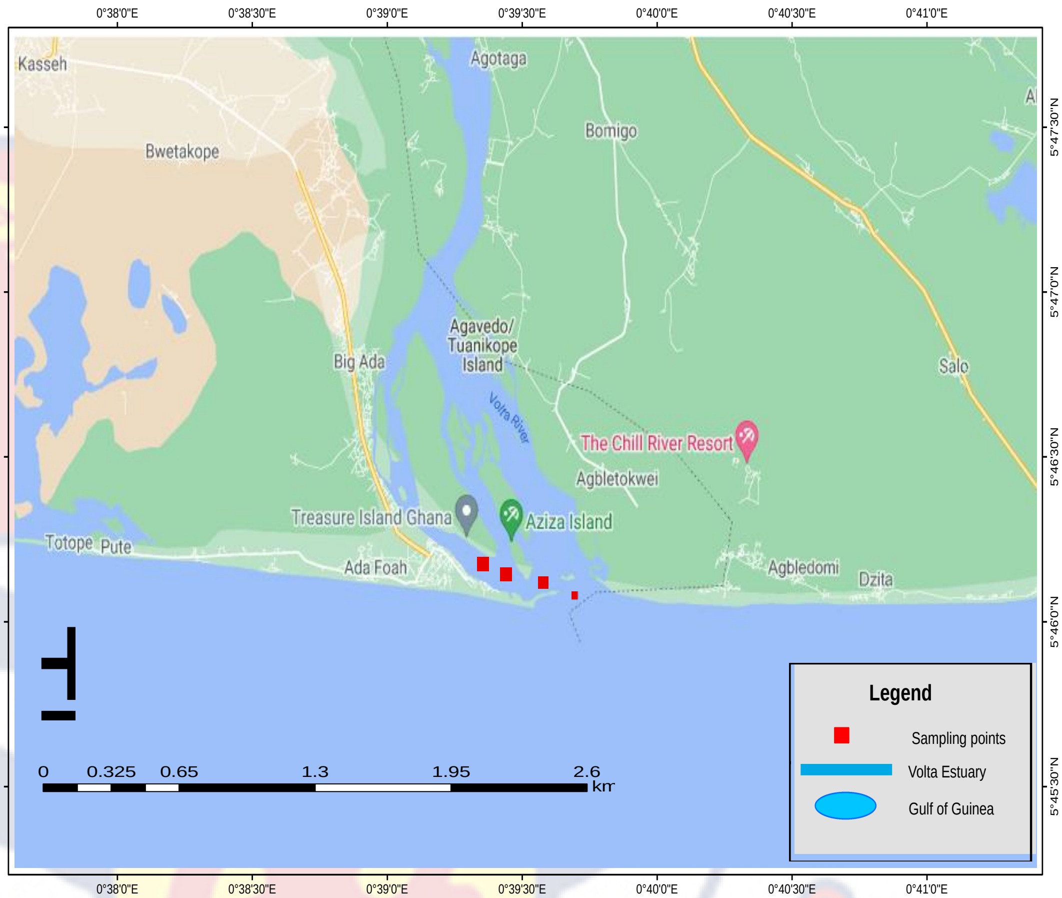


Figure 5: Study area map showing the sampling locations in the study area

The study was conducted in the Volta River Estuary at Ada Foah. Ada Foah is a coastal town in the Dangme East District of the Greater Accra Region. The town is located on a barrier adjacent to the Volta River Estuary, sandwiched between the Volta River on the east, Songor marshes on the west and the Atlantic Ocean on the south. The coastline of Ada is approximately 45 kilometres, stretching from Wekumagbe in the west to Azizanya in the east. Ada Foah spans a total land area of approximately 909 km^2 (Kusimi & Dika, 2012). To the North, Ada Foah is surrounded by the North Tongu District, to the east by South Tongu District, to the west by Dangme West District and to the south by the Gulf of Guinea (Ayerteye & Atteh, 2020).

Two principal winds influence Foah: the south-westerly monsoon winds that bring rainfall from the Gulf of Guinea and the north-easterly harmattan winds that blow across the Sahara Desert to the coast, bringing dry, dusty conditions during the dry season.

The vegetation is largely coastal savannah, with short savannah grasses and shrubs, as well as a few small trees, spread throughout the landscape. Coconut palms and mangrove tree strands can also be found growing along the shore, particularly near the Songor Lagoon and the Volta River delta.

The economy of the district is predominantly agricultural. Agriculture, which serves as the principal source of income for the majority of the population, employs approximately 51 percent of the adult population. Agricultural operations include crop cultivation, livestock production, and fishing, to name a few examples. Aside from agriculture, fishing, mining for salt, sand and gravel is a significant source of income in the region's economy (Bolle *et al.*, 2015).

Ada Foah is known as the tourism capital of the Ada East District due to the presence of beaches, estuary, and other tourism-related attractions and services. Because of the river and the ocean, Ada Foah is well-known for water sports like swimming, sailing, fishing, and boat cruises.

The Volta River is the major surface water source in the area. It flows along the district's southern and eastern borders. The river is now braided into three main channels: west, east, and between the eastern and western channels. Tuanikope and

Gravedome are on the eastern side of the canal, while Ada-foah, Azizanya, Agokpo and Big Ada are on the western side. Afrive, Adzim, Kudekekope, Alorkpem, and Azizakope are islands in the middle channel.

3.2 Species Studied

Water lettuce and water hyacinth, two of the most common floating aquatic weeds, were studied. While each has advantages, they also have drawbacks that can be damaging to the aquatic ecology.

3.3 Research Design

An experimental research design was employed in this study. A simple Random Sampling technique was carried out. The research design for the experiment with a single factor (cow dung) and two factor levels (water hyacinth and water lettuce) was a "Factorial Design." Specifically, it was a 2x1 Factorial Design.

A factorial design is a type of experimental design that allows researchers to investigate the effects of two or more independent variables (factors) simultaneously on a dependent variable. In this case, the two factors are the types of biomasses (water hyacinth and water lettuce), each with one level, and the single factor is cow dung.

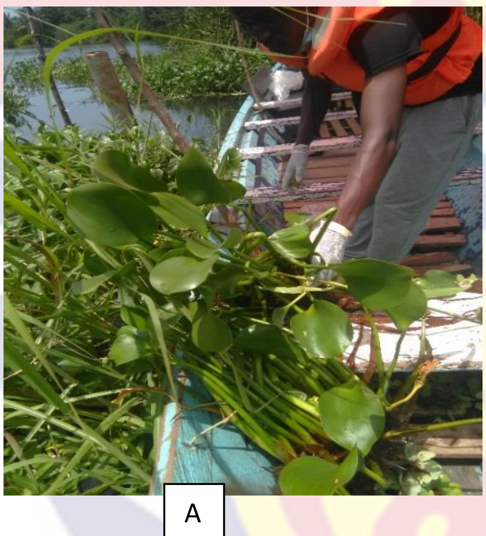
3.4 The Data Source

The data for this study came from primary sources. The anaerobic digestion parameters (temperature and pH), the daily biogas yield and compositions were all gathered from this study. Additionally, chemical compositions of the two substrates were gotten through this study.

3.5 Sample Collection, Processing and Experimental Procedure

3.5.1 Harvesting

Harvesting of the weeds was done manually in a boat. The weeds were collected in a boat on a 15-day interval for 3 90 days from the estuary and submerged in the sample water, in insulated chests for storage and processing. This was done to mimic the aquatic environment and to ensure that the weeds remained undigested until they were transported to the laboratory for additional analysis.



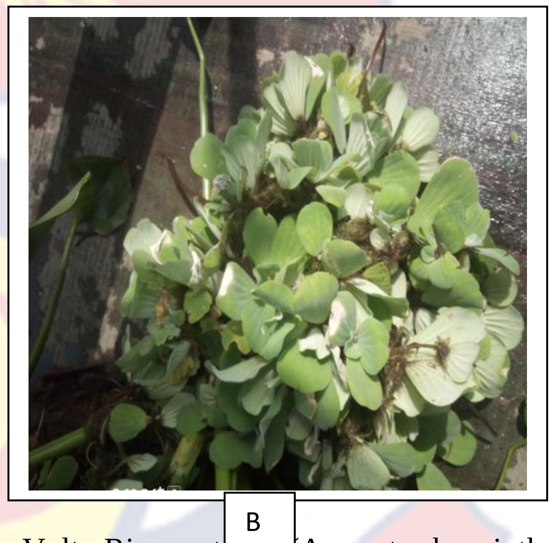


Figure 6: Collection of weeds from the Volta River estuary (A= water hyacinth, B= water lettuce

3.5.2 Chemical Composition Analysis of the Water Lettuce and Water Hyacinth

Following cleaning, the plant samples were separated into three portions; the leaves, the petioles, and the roots, for further examination The plant samples were analysed for their chemical and elemental composition (Moisture Content, Ash content, Oil/ Fat Determination, Nitrogen and Protein Determination, Crude Fibre Determination, Organic matter, Volatile solids, Determination of N, K, Na, Ca, Mg, P, Zn, Cu & Fe) using standard protocols (AOAC International, 2016), American Society for Testing and Materials (ASTM D121, ASTM D 3173-17, ASTM D 3175-17, ASTM D 3172-13, and ASTM D 3174-12).

Thorough understanding of physical and chemical characteristics is needed to be able to utilize weeds such as water lettuce and water hyacinth as feedstocks or substrates for the generation of biogas. Physicochemical qualities are critical parameters because they influence the properties of these raw materials during the anaerobic conversion process and output of methane.

3.5.3 Moisture Content

The porcelain crucibles were cleaned, dried, and weighed before being placed in the oven. Fresh samples weighing 10-12 g were weighed in oven-dried crucibles that had been cleaned. Evenly, the crucibles were spread throughout the base of the oven in order to achieve heat dispersion. The samples were then allowed to heat for 48 hours at 105 degrees Celsius in the oven. Once this period was completed, samples were removed and placed in a desiccator before being weighed. For each sample, the procedure was repeated three times. The percentage water loss by the sample was used to calculate the moisture content of the plant.

3.5.4 Ash Determination (Sluiter et al., 2008)

Ash content is a measurement of the amount of minerals and other inorganic material in biomass and is used in conjunction with other techniques to ascertain the complete composition of biomass sample.

For close to an hour, dried weed samples were heated gently at 105°C in an oven before being transferred into a furnace. The samples were allowed to burn in the furnace overnight, where heating continued until all of the carbon particles were burned away. The crucible containing the sample was taken out, cooled in a desiccator and weighed. The ash content was then determined as the proportion of the original sample.

3.5.5 Oil/ Fat Determination

50 of 10 mm Soxhlet extraction thimble was filled with around 10- 12 g of the milled samples. Weighing a clean, dry 250 ml round bottom flask About 150ml of petroleum spirit was added and transferred to the Soxhlet extractor for 6 hours of extraction utilizing a heating mantle as a source of heat. At the end of 6 hours, the flask was taken out and positioned in a 60°C oven for two hours. The spherical bottom flask was removed, desiccated, and weighed. The fat/oil proportion was computed as follows.

Calculation

$$\text{Crude Fat (\%)} = \frac{\text{W (g)}}{\text{Sample (g)}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where W is Weight of Oil

3.5.6 Nitrogen and Protein Determination

The protein content of food is estimated using the nitrogen concentration of the meal. The protein was determined using the kjeldahl. The procedure is broken down into three steps: digestion, neutralization or distillation, and titration.

- **Digestion**

A 100 ml Kjeldahl flask was filled with 0.2 g of the material. The samples were digested at 360°C for two hours after 4.4 mL of digestion reagent was introduced. A blank was made in the same manner. Following digestion, the digests were placed into 50 ml volumetric flasks and made up to volume.

- **Distillation**

A steam distillation apparatus was set up. For around twenty (20) minutes, the distillation apparatus was flushed with distilled water. After flushing the equipment, five (5) millilitres of boric acid indicator solution were transferred into a 100 ml conical flask and positioned beneath the distillation apparatus's condenser, with the tip of the condenser completely submerged in the boric acid solution. Through the trap funnel, an aliquot of the sample digest was delivered to the reaction chamber. To begin distillation immediately, 10 mL of alkali mixture was added, and approximately 50 mL of the distillate was collected.

- **Titration**

The distillate was titrated with 0.1N HCl solution until the solution changed color from green to the indicator's initial wine-red color. Digestion blanks were treated similarly and deducted from the titre value of the sample. The resulting titre values were used to compute the nitrogen and thus the protein content. 6.25 was the conversion factor used.

%Total Nitrogen (%N) =

$$\frac{(\text{Sample titre value} - \text{Blank titre value})\ X\ 0.1\ x 0.01401\ x\ 100}{sample\ weight\ X\ 10} \ldots\ldots\ldots\ (2)$$

% Protein = %N x 6.25

3.5.7 Crude Fibre Determination

1 g of the sample was weighed and transferred to a boiling flask. After that, 100 ml of the 1.25% Sulphuric acid was heated for 30 minutes. Filtration was then carried out in a sintered glass crucible that was numbered. Following filtration, the residue obtained was returned to the boiling flask and 100 ml of 1.25% NaOH solution was added before boiling for 30 minutes. When the boiling was done, the residue was washed with hot wat and methanol. The crucible was then dried weighed and dried in an oven for 105 degrees overnight. For around 4 hours, the crucible was placed in a 500°F furnace. In a desiccator, the crucible was progressively cooled to room temperature before being weighed.

Calculation

$$\% \text{ Crude fibre} = \frac{\text{weight loss through ashing}}{\text{Sample weight}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

(AOAC, 2005)

3.5.8 Preparation of Sample Solution for the Determination of N, K, Na, Ca, Mg, P, Zn, Cu & Fe

The preparation of sample solutions for elemental analysis includes an oxidation method that is required for the elimination of organic components via acid oxidation prior to the performance of a full elemental analysis, which is conducted after the oxidation procedure is completed.

3.5.8.1 Colorimetric Determination of P using the Ascorbic Acid Method

Preparation of colour producing reagent and P standard solutions is required for the technique. Reagents A and B combine to generate the colour producing reagent. Reagent A consists of 12 g ammonium molybdate in 20 mL of distilled water, 0.2908 g potassium antimony tartarate in 100 mL of distilled water, and 1 L of 2.5M H2SO4. In a 2 L volumetric flask, the three solutions were mixed and made up to volume with distilled water.

1.56g of ascorbic acid was dissolved in 200 mL of reagent A to make reagent B. A 100gP/mL stock solution was made, from which a series of working standards of P with concentrations of 0, 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 g P/mL in 25 mL volumetric flasks were prepared. A 2 mL aliquot of the digested materials was pipetted into 25 ml volumetric flasks to give the samples and standards the same background solution.

After the addition of 10 ml of distilled water to the samples and standards, 4 ml of reagent B was added and their quantities were made up to 25 ml with distilled water and then thoroughly mixed. After allowing the flasks to stand for 15 minutes for colour development, the absorbances of the standards and samples were measured with a spectrophotometer at a wavelength of 882 nm. Using their concentrations and absorbances, a calibration curve was created. The standard curve was used to extrapolate the concentrations of the sample solutions.

Calculation

If C = μgP/mL obtained from the graph,

then μgP/g (sample) = $\frac{\text{C x Dilution Factor}}{\text{weight of sample}}$ …………………………….... (4)

3.5.8.2 Determination of Potassium

A flame photometer was used to measure potassium and sodium levels in digested samples. The following working standards of K were prepared for the determination: 0, 2, 4, 6, 8, and 10 g/mL Individually, the working standards and sample solutions were inhaled into the flame photometer and their readings (emissions) recorded. Using the concentrations and emissions of the working standards, a calibration curve was produced. Using their emissions, the concentrations of the sample solutions were estimated from the standard curve.

Calculation

$$\mu gK/g = \frac{C \text{ x solution volume}}{\text{Sample weight}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Stewarte et. al (1974)

3.5.8.3 Determination of Calcium and Magnesium by Edta Titration

In this process, the cations are chelated with ethylene diaminetetraacetic acid (EDTA). The process included determining calcium and magnesium together, as well as determining calcium alone and magnesium by difference.

An aliquot of 10mL of the sample solution was placed in a 250 L conical flask and the solution was diluted to 150ml with distilled water, 15 mL of buffer solution, and 1 mL each of potassium cyanide, hydroxylamine hydrochloride, potassium ferro-cyanide, and triethanolamine (TEA). The solution was titrated against 0.005M EDTA after five drops of erichrome Black T (EBT) were added. 10 mL of the sample solution was Pipetted into a 250 conical flask and diluted to 150 mL with pure water. This was used to quantify calcium. Also, 5 drops of calcon indicator were added to 1 mL of potassium cyanide, hydroxyl-amine-hydrochloride, potassium ferro-cyanide, and TEA, and the solution was titrated with 0.005M EDTA.

Calculations

$$\% \, Ca = \frac{0.005 \times 40.08 \times T}{\text{Sample wt}} \quad \ldots\ldots\ldots (6)$$

$$\% \, Mg = \frac{0.005 \times 24.31 \times T}{\text{Sample wt}} \quad \ldots\ldots\ldots (7)$$

where T = titre value

Page et al (1992)

3.5.8.4 Organic Carbon determination

Preparation of Standards

About 15 g of sucrose was dried in an oven at 105°C and then cooled in a desiccator. In a volumetric flask, 11.886g of dry sucrose was dissolved in water and made up to 100 ml. By the help of a pipette, 0, 5, 10, 15, 20 and 25 ml of the 50mg/ml C stock solution were transferred into marked 100ml flask and filled to the mark with water. It was made sure that it was properly homogenized. These are the working standards, with concentrations of 0, 2.5, 5.0, 7.5, 10.0, and 12.5 mg/ml C. Into 100 ml conical flasks, 2 ml of each working standard was pipetted and dried at 105°C. These now included 0, 5, 10, 15, 20, 25, and 50 mg C

Procedure

A labelled 100 ml conical flask was filled with 1 + 0.001 g ground soil (0.15 mm). The soil's weight, W, was measured. 10 ml of 5 % potassium dichromate solution was added and allowed to completely wet or dissolve the standards. A quick burette was used to add 20 ml of H_2SO_4 to the mixture, which was gently stirred. After cooling, 50 ml of 0.4% barium chloride was added, swirled to completely mix and left to stand overnight. At 600 nm, an aliquot of the clear supernatant solution was transferred into colorimeter cuvette and the absorbance of each standard and sample was measured and recorded.

Calculation

The absorbance was plotted against the concentration on a graph. Using the solution concentrations for each unknown and the blanks, the mean blank value was subtracted from the unknowns, yielding a value for corrected concentration, denoted by the letter K.

$$\% \text{ Organic carbon} = \frac{X \times 0.1}{W \times 0.74} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Organic Matter = Organic carbon x 1.724

3.5.8.5 Nitrogen Free Extracts (NFE)

Nitrogen Free Extracts (NFE) is the sole component of Proximate Analysis which is determined by a calculation.

Thus % NFE = 100 – (% water + % CP + % CF + % Ash + % EE) % water + % CP + % CF.

3.6 Sample Collection, Processing, and Preparation for Anaerobic Digestion

3.6.1 Biogas Plant

The study utilized a portable continuous digester located on the premises of Das Biogas and Construction Limited. This Plant has a capacity of 1000 L and is equipped with a Plastic Tank and other accessories. It was a square plant with a 1m^3-by-1 m^3 footprint. On the ground, this portable plant was placed. The Plant was connected to a separate balloon for the storage of produced biogas. The bio-digester was painted black. The purpose of painting the biodigester black was twofold: to restrict light penetration and to retain the heat accumulated during the day.

Figure 7: Portable continuous biogas plant

3.6.3 Inoculation

An inoculum is an excellent source of bacteria (Fulford, 1998). Inoculums are biologically active liquids or partially digested organic waste mediums that are high in microorganisms (Dennis, 2015).

Anaerobic inoculum (cow dung) was obtained from a cow shelter in Juaben, Kumasi, for digester starting. A reasonable amount of clean water was mixed with 50 kg of the cow dung (inoculum) with the aid of the hand. The mixture was then charged into a 1000 L capacity biodigester which was then topped up with clean water till it reached the 900 L line. The pH of the mixture was recorded with the aid of a pH meter. The biodigester containing a combination of cow dung and water was left standing for a period of 5 days. This time is crucial for the anaerobic digestion process to occur effectively and efficiently. When the inoculum is added to the biodigester, it begins to acclimate to the new environment and establish itself as the dominant microbial community. On the sixth day, the valve on the digester was opened a match was lighted near the valve. A flame indicated the presence of biogas that may have accumulated inside the digester. This also indicated the activity of anaerobic microorganisms and the successful initiation of the digestion process. However, other test such as pH measurements and measurement of other critical parameters such as Volatile fatty acids can also be done. At this point the feedstocks can now be introduced into the digester.

3.6.4 Monitoring and Operational Activities

Following a successful inoculation, the smooth operation of the digester must be maintained by performing certain monitoring operations. The plant was fed on a daily basis, the mixing container cleaned, the digester stirred or agitated on a regular basis, and monitoring of gas pressure. There was daily recording of gas output, temperature, and slurry pH. Cleaning and inspecting of gas appliances were done on a weekly basis. Gas valves were examined, fittings, and appliances were checked for leaks. Monitoring of the formation and eradication of scum was carried out. The plant was also examined for its ability to keep water and gas.

Figure 8: A= Checking for leakages on the balloon, B= Sealing of leakages on the reactor

3.6.5 Quantifying the Weight of Substrate Going into the Digester

This is a critical step in the biogas production process. Accurate measurement of the substrate weight allows for the precise control of the organic loading rates (OLR) which is essential for efficient and stable biogas production. The OLR was calculated as the amount of organic matter fed into the digester per unit volume of the digester per day.

$$OLR\ (kg\frac{VS}{m3}/day) = \frac{mass\ of\ organic\ matter\ (kg)}{Digester\ Volume\ (m3) \times Digestion\ time}$$

The substrate flow rate which is the rate at which the feedstock or substrate is continuously or intermittently added to the digester was also calculated and expressed in terms of Volume per unit time (Litres/day).

A weighing scale was used to measure the amount of feedstock placed into the biodigester. Typically, the quantity of substrate (weeds) introduced into the digester was measured in kilograms. The values were recorded and replicate readings were also taken.

Figure 9: Measuring of weed samples

3.6.6 Pretreatment

The act of reducing the average particle size of solids to smaller sizes is what is referred to as comminution. It can be achieved through the use of crushing, grinding, cutting, vibrating, or other processes (Gupty, 2003; Kanda and Kotake, 2007). Comminution of the weeds was accomplished by pounding them in a mortar and pestle. It is well established that decreasing the size of particles and increasing their specific surface area resulted in an increase in gas production, particularly when digesting substrates containing a large proportion of slowly biodegradable components (Nalinga and Legonda, 2016). Thus, pounding the weeds can assist in increasing the surface area of contact between the microorganism and the fermentation substrate during anaerobic digestion.

Figure 10: Pretreatment of weeds by pounding

3.6.7 Mixing/Homogenizing

2.5 kg of the pounded water hyacinth was amalgamated with 2.5 kg of clean water to form a slurry.

3.6.8 Feeding of weeds into Anaerobic Tanks

The mixture was then charged into the biodigester. The process was repeated every day for 45 days.

3.6.9 Anaerobic Digestion

After charging of the biodigesters, digestion took place in the absence of oxygen. The digester was thoroughly checked to ensure that it was both water- and airtight to avoid seepage of water and biogas into the air. It was ensured that the digester was well-insulated to maintain a constant temperature for digestion.

3.6.9.1 Measuring Digester Conditions

3.6.9.1.1 Temperature of the Digester

The digester's temperature was checked three times a day and the readings recorded. It was essential to know the temperature in the digester because it is an indicator that can be used to determine how stable the digestion process is.

3.6.9.1.2 pH measurement

Despite the fact that methanogens consume organic acids as part of their diet, they cannot endure for long in an acidic environment. The ideal pH range is between 6.5 and 8, with pH of 7.2 being the desired value (Jacob, 2009). For the 45-day digestion period, daily pH readings were taken using a pH meter. These readings were taken in triplicates.

Figure 11: CH_4/pH meter used for the measurement of the pH

3.6.9 Biogas production

After days of digestion, biogas was produced and stored in balloons. Before being stored, the gas volume and composition were measured and recorded.

3.6.9.1 Measurement of the Biogas and Methane

A flowmeter was used to measure the volume of biogas (Puxin Ultrasonic biogas flow meter BF-2000). The flowmeter was connected to the biodigester to measure both the daily and cumulative amounts of biogas generated. By the use of a biogas analyzer, the percentage of methane in the gas generated was determined.

(a) (b)

Figure 12: (a): Puxin Ultrasonic biogas flow meter BF-2000 used for the measurement of the volume of biogas

(b): Biogas analyser for CH_4 measurement

3.7 Sludge production

When microorganisms degrade the weeds and biogas is generated, a left-over slurry is discharged through the outlet of the digester. This digestate is collected and stored for further use as a fertilizer.

3.8 Summary of Experimental Set up

A reasonable amount of clean water was mixed with 50 kg of the cow dung (inoculum) with the aid of the hand. The mixture was then charged into a 1000 L capacity biodigester which was then topped up with clean water till it reached the 900 L line. The pH of the mixture was recorded with the aid of a pH meter. The biodigester containing a combination of cow dung and water was left standing for a period of 5 days. This time is crucial for the anaerobic digestion process to occur effectively and efficiently. When the inoculum is added to the biodigester, it begins to acclimate to the new environment and establish itself as the dominant microbial community. The digester was fed with a mixture of 2.5 kg of water hyacinth and 2.5 L of clean water on the 6th day. To ensure a successful biogas production and avoid issues during startup, it was necessary to add the co-substrate within a relatively short period after introducing the inoculum. Any significant delay in adding the co-substrate would result in the microbial community not having enough organic matter to feed on, leading to decline in microbial activities. The delay could also result in increased ammonia concentrations and pH fluctuations in the biodigester. Also, the basis for mixing 2.5 parts of water hyacinth or water lettuce with 2.5 parts of water is to create a slurry or mixture with the appropriate solids content for anaerobic digestion. A well-balanced total solids content is crucial for optimal microbial activity and influencing the biogas yield.

The charging of biodigester with the water hyacinth was done on a continuous basis for a period of 45days with the same quantity of the weeds and water. During the 45days digestion period, total gas volume and composition were monitored daily by the use of gas flow meter and gas analyser, respectively. Temperature, pH, gas yield, and gas compositions and chemical compositions taken and recorded.

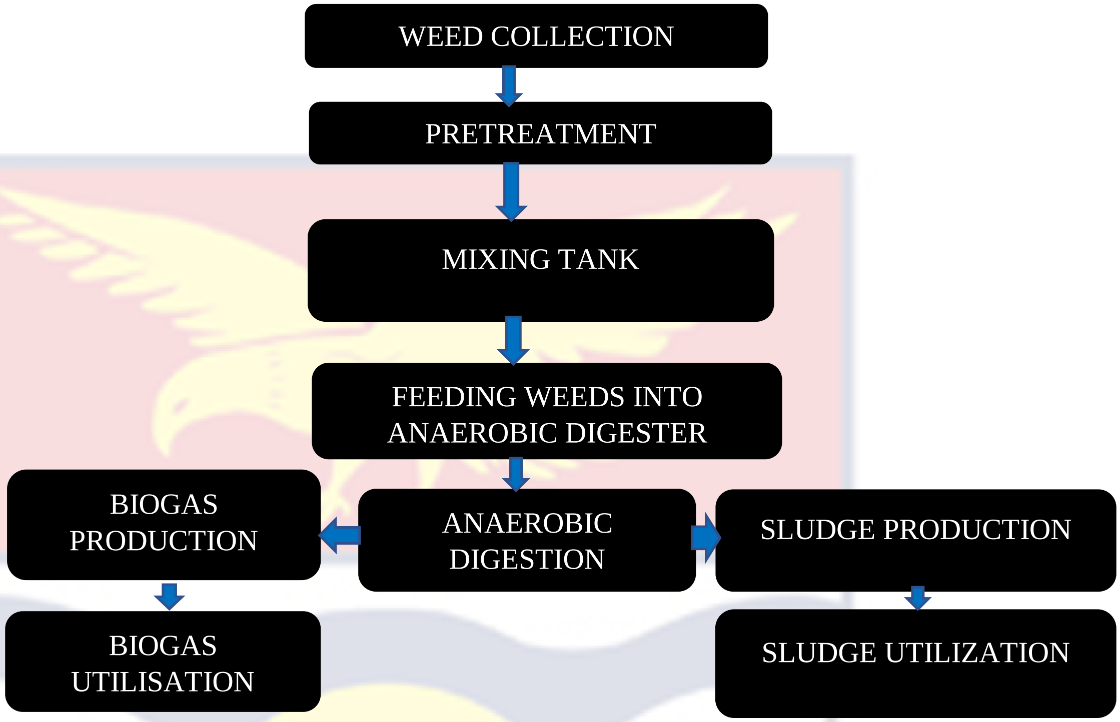


Figure 13: Summary of experimental procedure

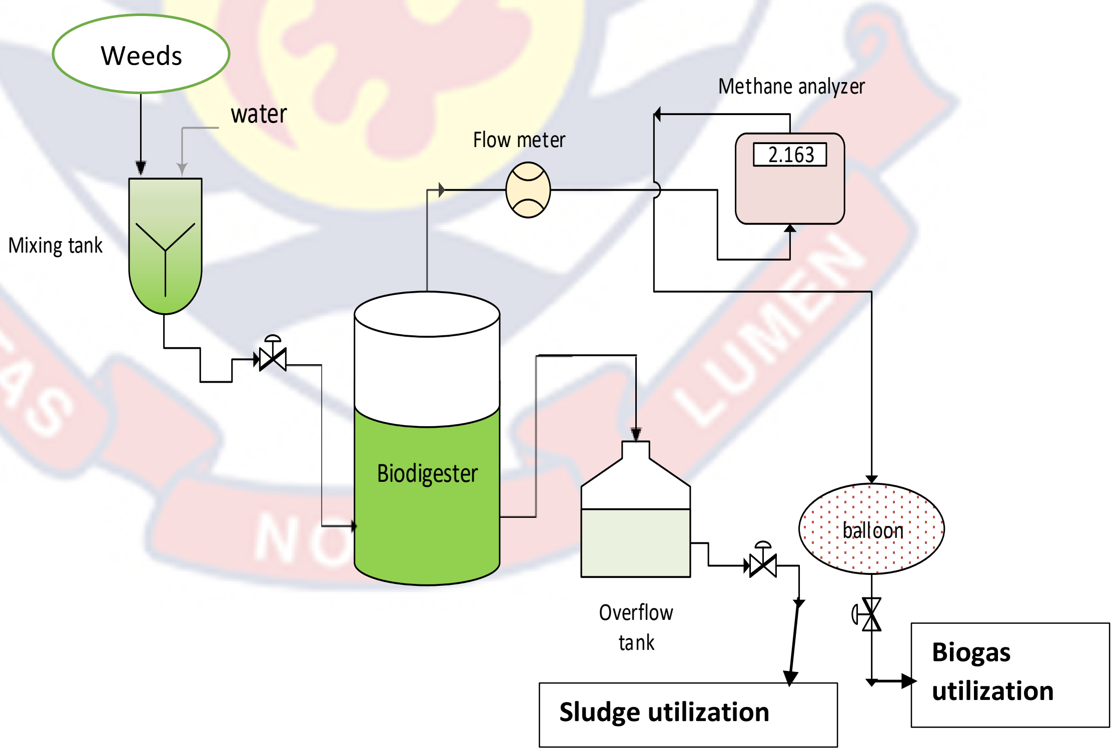


Figure 14: Schematic representation of the experimental set-up.

3.8 Statistical Analysis

An adequate analysis of variance (ANOVA) was performed on the data. To compare the means of the significant source effects, the student's t-Test and z-Test were calculated at a 5% significance level. Bar charts were also drawn to graphically represent the results obtained. This was carried out with the help of the Microsoft Excel Spreadsheet Application

CHAPTER FOUR

RESULTS AND DISCUSSION

Introduction

In this chapter, the empirical findings are presented, analysed and discussed in relation to supporting existing literature. Firstly, results of the chemical composition of the study species are presented. After that, gas yield and gas compositions are displayed in form of charts and tables. These results are later discussed in great detail. The final section of this chapter gives a summary of major findings.

4.1 RESULTS

4.1.1 Chemical and Elemental Analysis

4.1.1.1 Water Hyacinth Composition

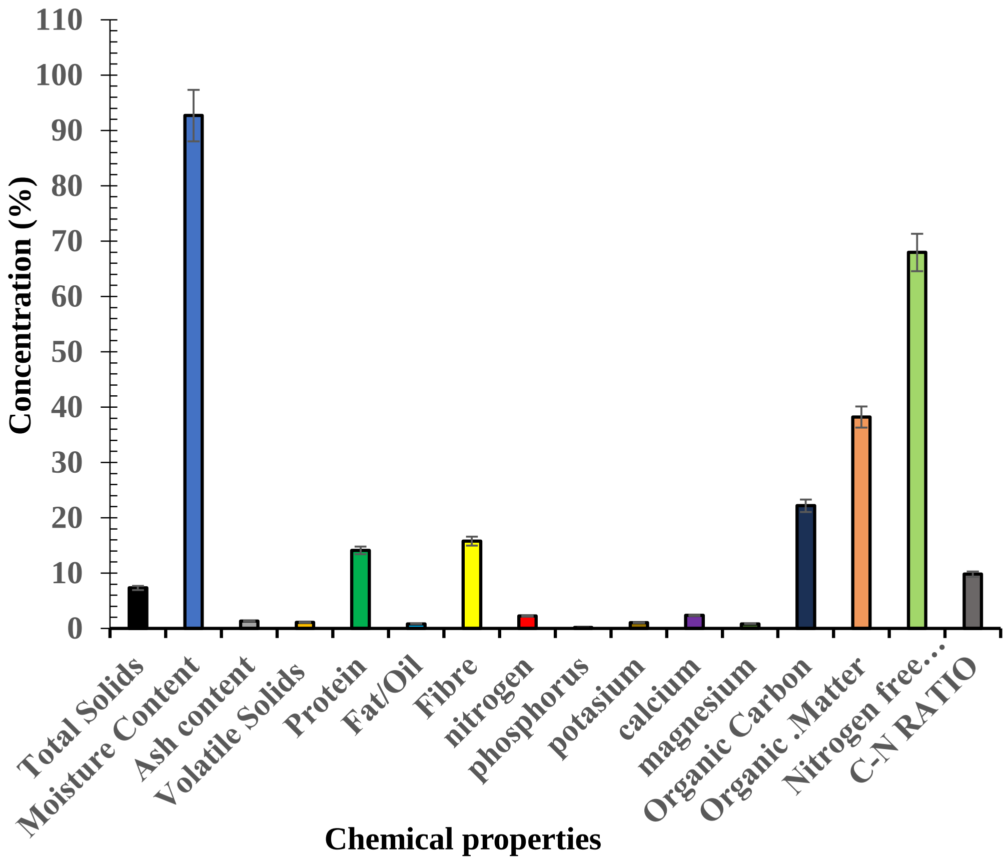


Figure 15: Chemical composition of water hyacinth

Several chemical constituents including elemental compositions were analysed and replicated for three times. The mean results mean results that were computed gave different or diverse values for the elements present in the Water Hyacinth plant. The outcome of the test showed that the moisture content of Water Hyacinth is very high with a value of 92.68% ± 0.05. With regards to the elemental constituents, carbon was the highest with a mean value of 22.17% ± 0.12. The nitrogen, phosphorus and potassium were below 4%. The Carbon-Nitrogen of the plant was 9.8208 ± 0.05.

4.1.1.2 Water Lettuce Compositional Analyses

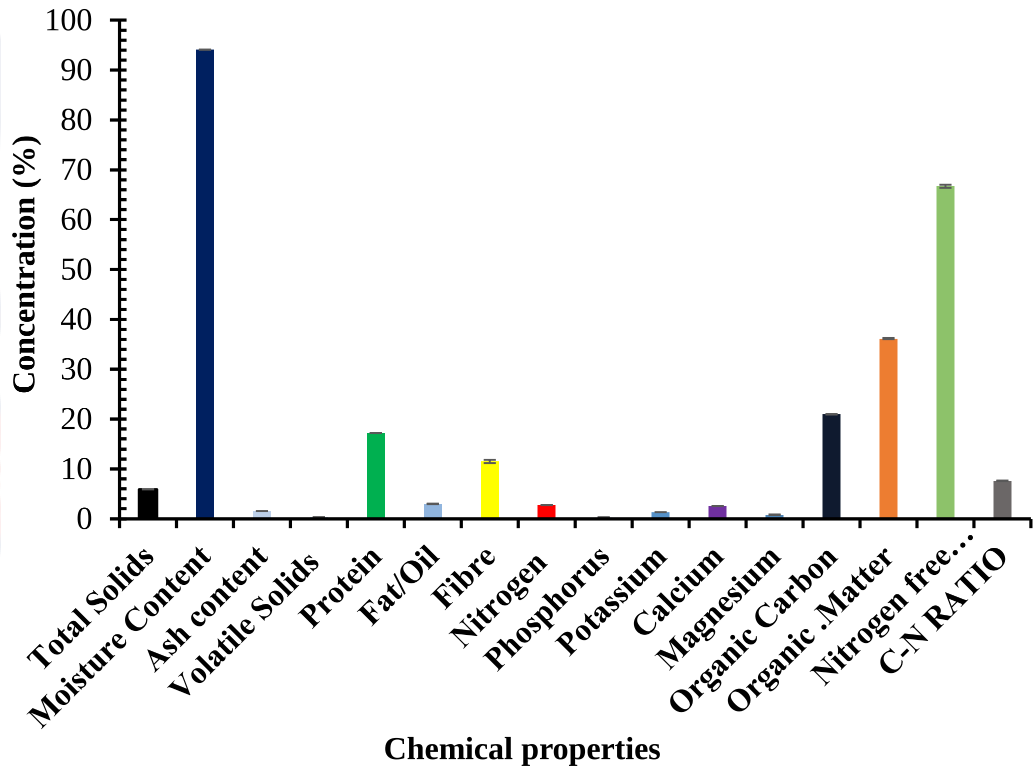


Figure 16: Chemical and elemental properties of water lettuce in percentages

Several chemical constituents, including elemental compositions, were tested in triplicate, with the mean findings revealing variable compositions. Water Lettuce had a high moisture level, according to the findings. Carbon was the most abundant elemental constituent, with a mean value of 20.9 percent 0.06. Nitrogen, phosphorus, and potassium levels were all less than 4%. The plant's C/N ratio was 7.60 0.05.

4.1.2 Measurement of Biogas and Methane Production

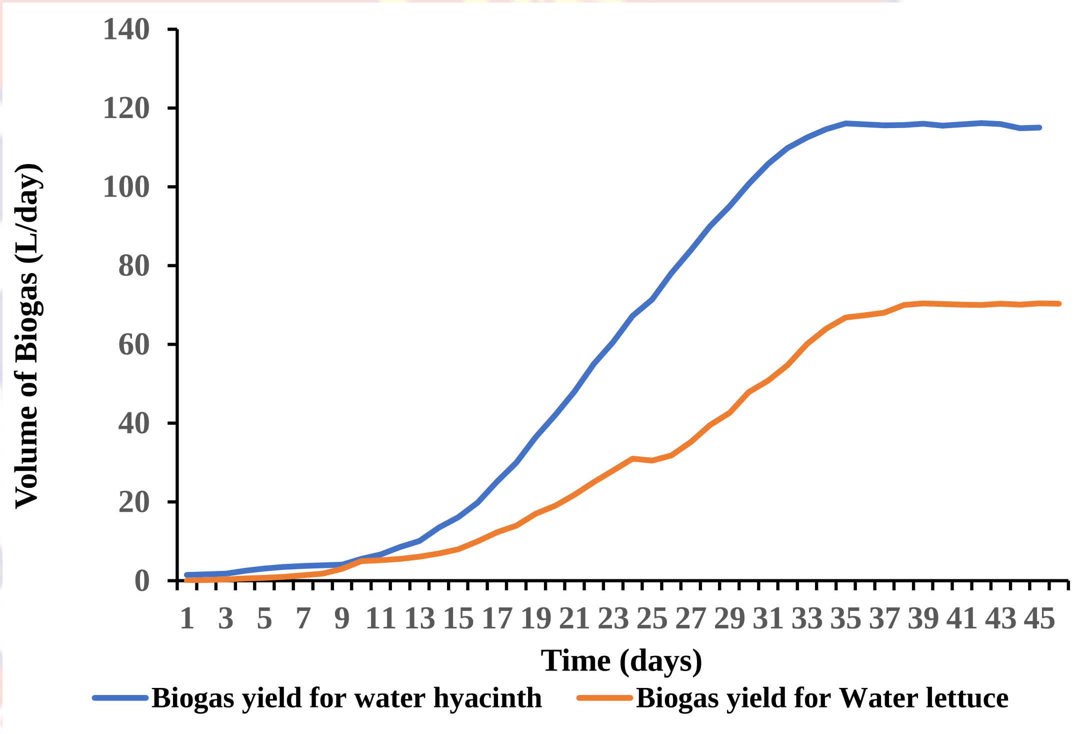


Figure 17: Graphical view of the biogas yield from the two substrates.

Over the digestion period, the volume of gas produce as a result of the degradation or breakdown of water lettuce and water hyacinth was measured daily and the line graph above shows the cumulative production of the gas. It can be deducted from the graph that, at the initial stages, thus first few days of digestion, production of gas was minimal but steadily increased as the digestion progresses.

The water hyacinth produced a cumulated biogas yield of 116.20L whereas that of the water lettuce was 70.40L.

Table 4: Comparison of the Mean Volume of Biogas Produced by Water Hyacinth and Water Lettuce Using ANOVA.

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	17634.40	1	17634.40	11.80	0.000904	3.95
Within Groups	131490.22	88	1494.21			
Total	149124.62	89				

Using a 95% confidence interval, ANOVA test was performed to compare the biogas yields of the two substrates and to determine whether there is a statistical difference between the means of the values obtained. With the p-value of (0.000904), the null hypothesis is rejected which means that there is actually a significant difference between the mean volume of gas produced by the two weeds.

Table 5: Comparison of the Mean Volume of Biogas Produced by Water Hyacinth and Water Lettuce Using Z-Test

	Water Hyacinth	**Water Lettuce**
Mean	60.09777778	32.10222222
Known Variance	2238.752495	749.661589
Observations	45	45
Mean Difference	0	
z	3.435381399	
P(Z<=z) one-tail	0.00029586	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	0.00059172	
z Critical two-tail	1.959963985	

To further prove and ascertain whether there was a significant difference in the means of the values obtained for both water hyacinth and water lettuce, a z-Test was performed. From the table above, it could be seen that the test score (calculated z-value) was greater (3.34) than the critical value (1.96). The critical value is the value that separates the Acceptance Zone from the Rejection Zone, thus to fail to reject or reject the null hypothesis. When the calculated z value is greater than the critical z-value, then it implies that the test score is in the rejection zone. On the other hand, if the test result is smaller than the Critical Value, it indicates that the test score is in the Acceptance Zone and we fail to reject the null Hypothesis. Hence, from the results stated above from this study, the null hypothesis is rejected. In simple terms, this means that the amount of biogas produced by the two weeds is statistically different.

4.1.3 Biogas Composition

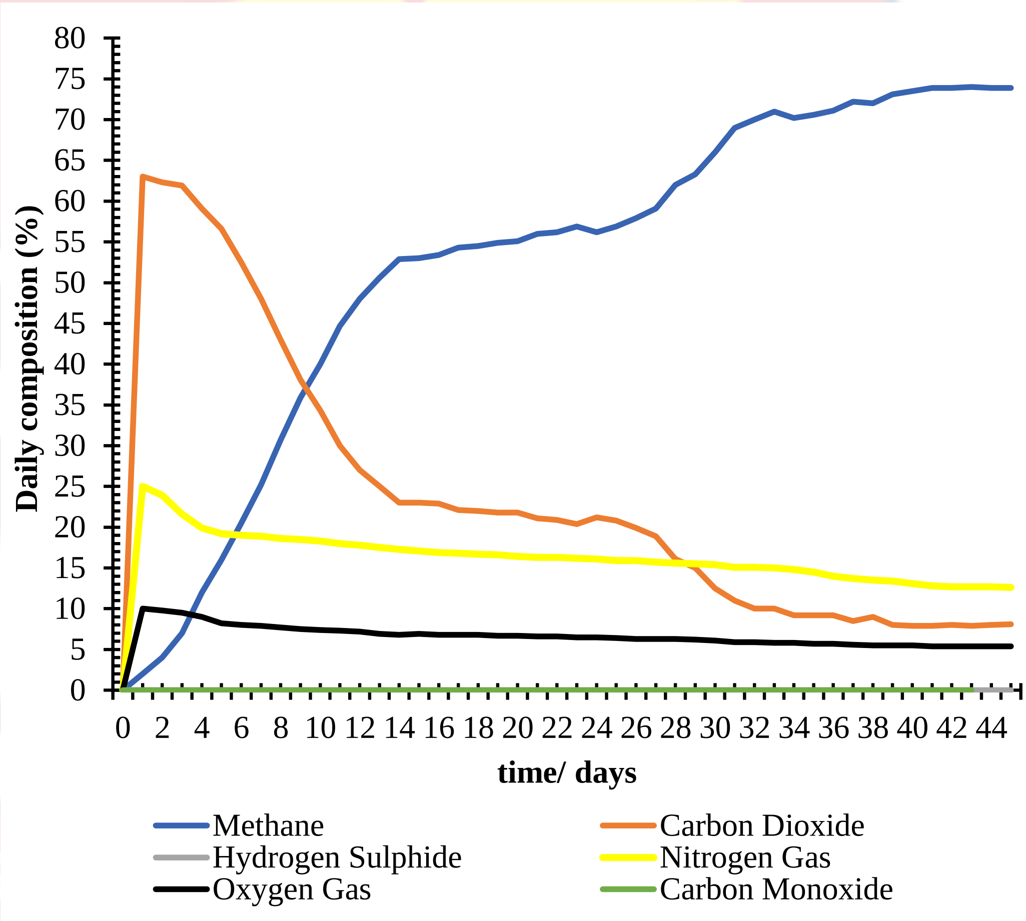


Figure 18: Daily composition of biogas produced from the biodigester containing water lettuce

Daily gas compositions were taken to monitor the changes occurring in the biodigester in terms of gas composition. The first few days of charging the biodigester with the substrate, showed high carbon dioxide concentrations with a minimal methane content. The nitrogen and oxygen gases were also quite high within the first few days but gradually declined as the days go by.

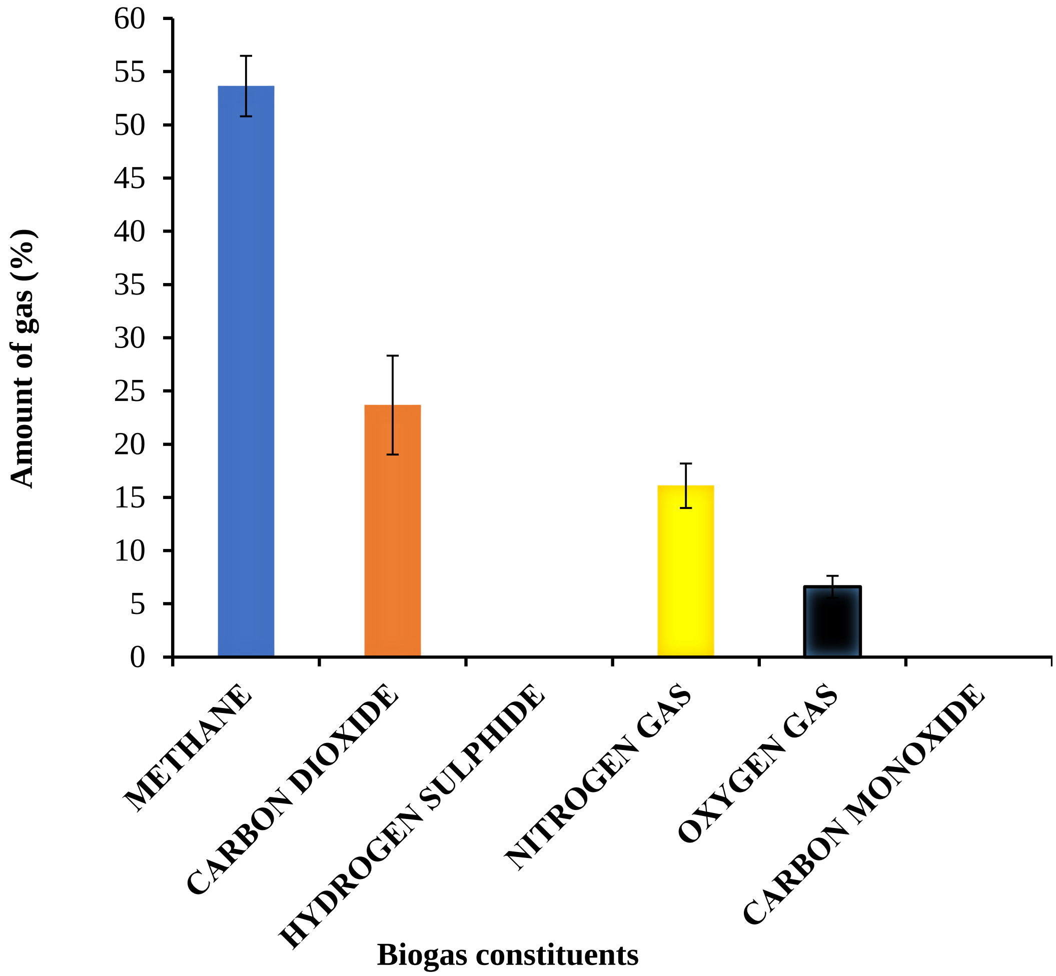


Figure 19: Mean percentages of the different components of the biogas produced during the digestion of water lettuce.

Methane was found to make up 53.63% 2.84 of the total biogas produced over the course of 45 days. Carbon dioxide was discovered to be 23.67% 4.66. The biogas contained very little hydrogen sulfide and carbon monoxide, with both measuring a mean value of 0.00 0. During the anaerobic digestion process, nitrogen gas and oxygen gas were also released, with mean values of 16.10 2.10 and 6.60 1.04, respectively.

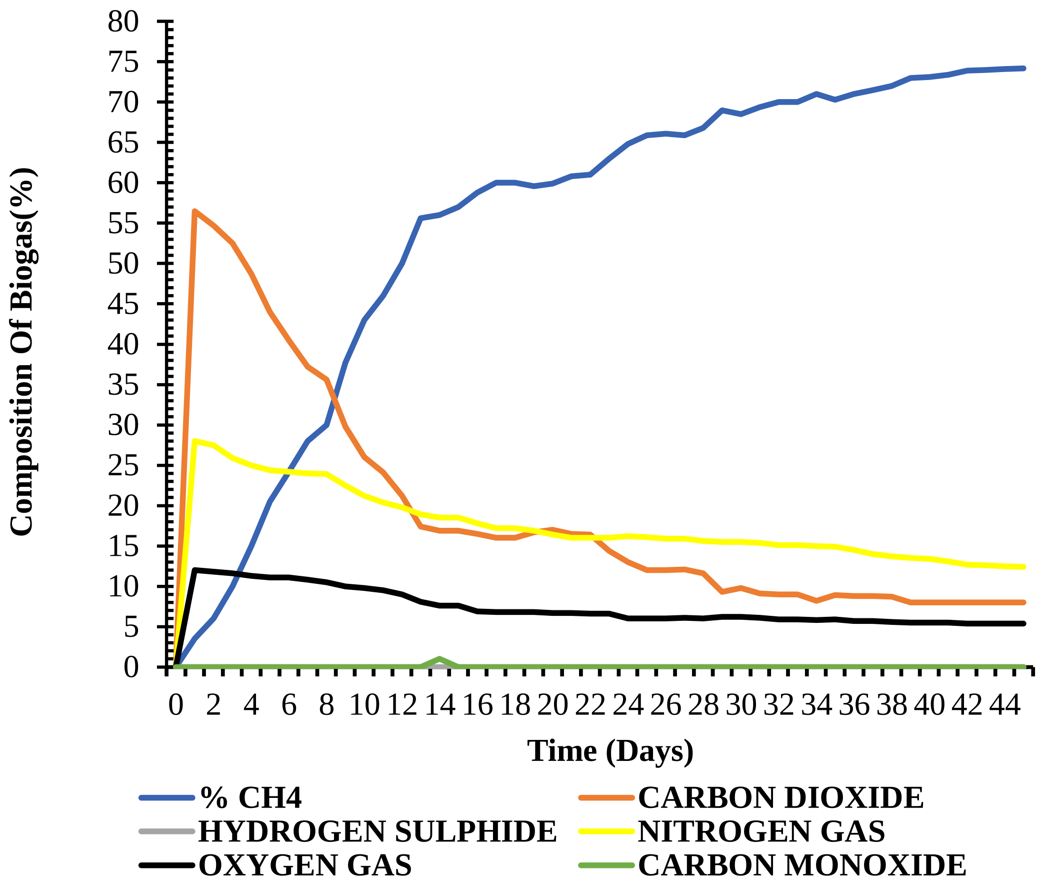


Figure 20: Daily composition of biogas produced from the biodigester containing water hyacinth.

Daily readings of biogas composition were taken in the digester containing water hyacinth. Methane production started on a rather slow level but appreciated during the course of the digestion. On the other hand, Carbon dioxide, Nitrogen gas and Oxygen gas had maximum values within the first few days of charging the biodigester. The levels however declined gradually over the digestion period.

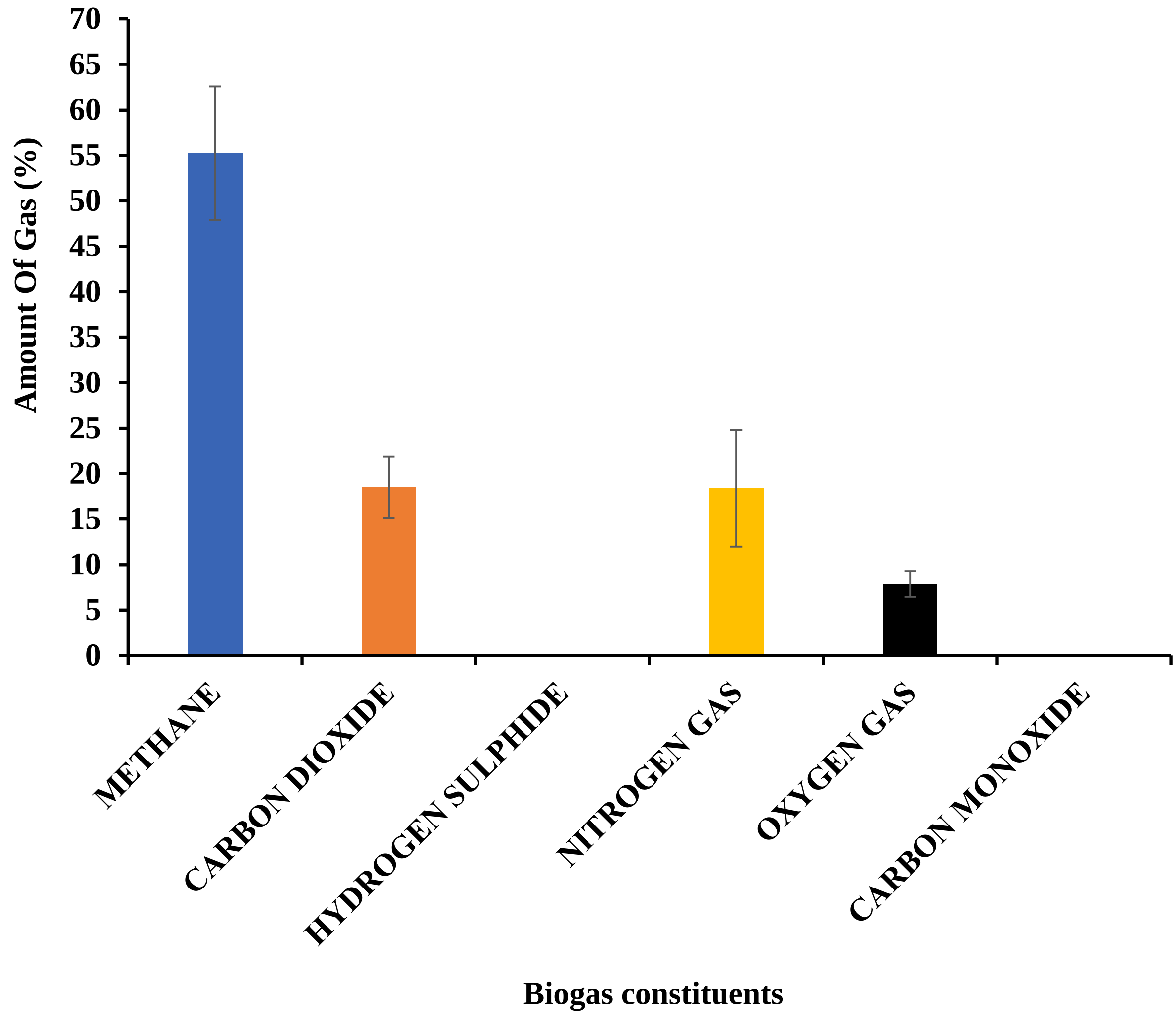


Figure 21: Graphical representation of the mean percentages of the different components of the biogas produced from water hyacinth.

Averagely, the menthane content of the biogas produced in the water hyacinth digester was 55.23% ± 7.32. The rest 44.77% of the biogas was composed of 18.5% ± 3.36 carbon dioxide, 18.4% ± 6.42 Nitrogen gas and 7.9% ± 1.42 Oxygen gas. There was little to no production of hydrogen sulphide due to the fact the gas was passed through a desulphurizer before measurements were taken.

5.1.4 Other Anaerobic Digestion Factors

Temperature

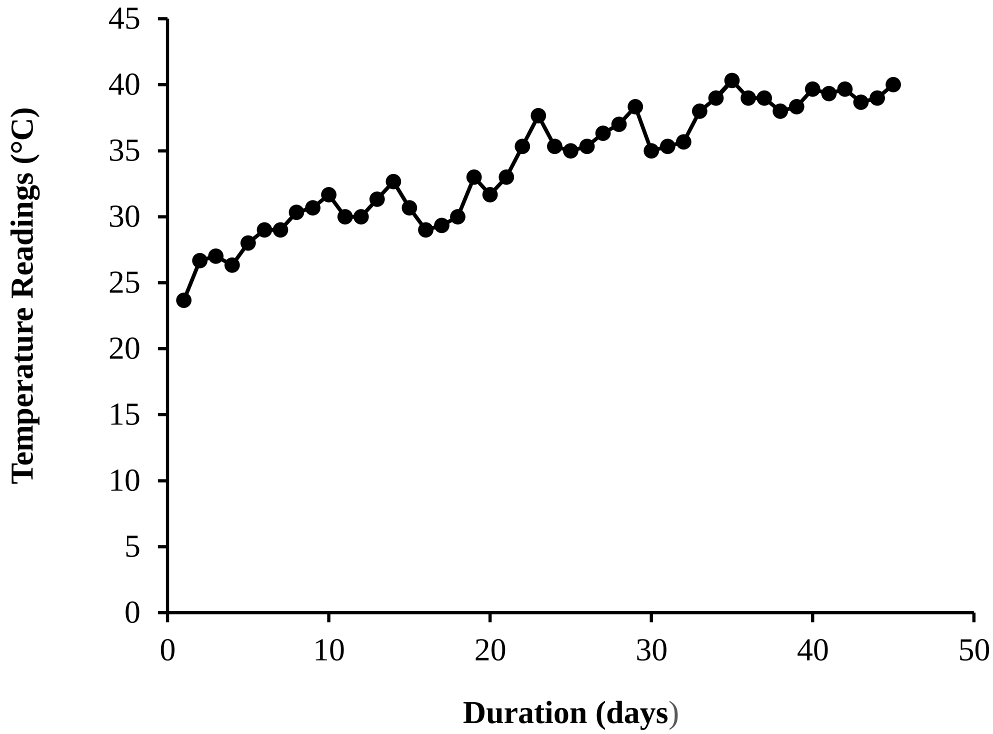


Figure 22: Daily temperature readings in the digester containing water lettuce.

The digester was operated at mesophilic conditions. The maximum temperature recorded was 40 °C and an overall mean value of 33°C

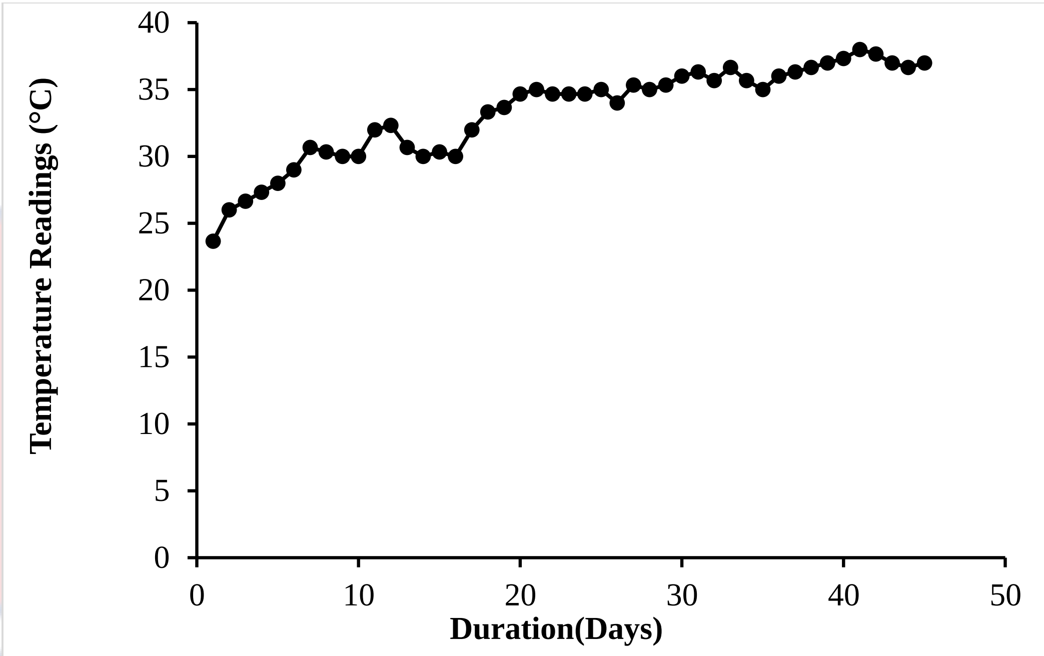


Figure 23: Daily temperature readings in the digester containing water hyacinth. The maximum temperature recorded was 38 °C and an overall mean value of 33°C

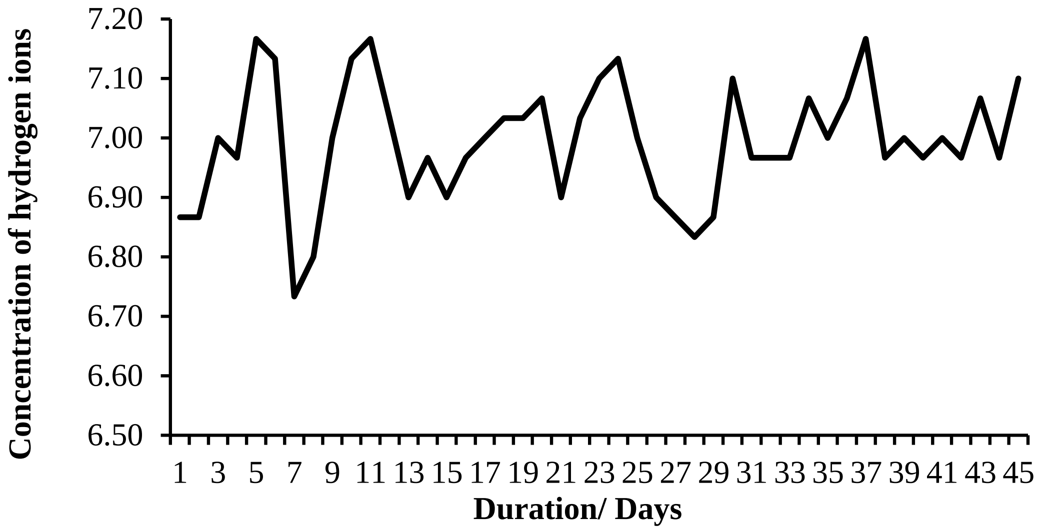


Figure 24: Daily pH readings in the biodigester containing the water Lettuce

Within this digester, pH fluctuations were within the acceptable range for anaerobic digestion. The pH range of approximately 6.70-7.10 was observed

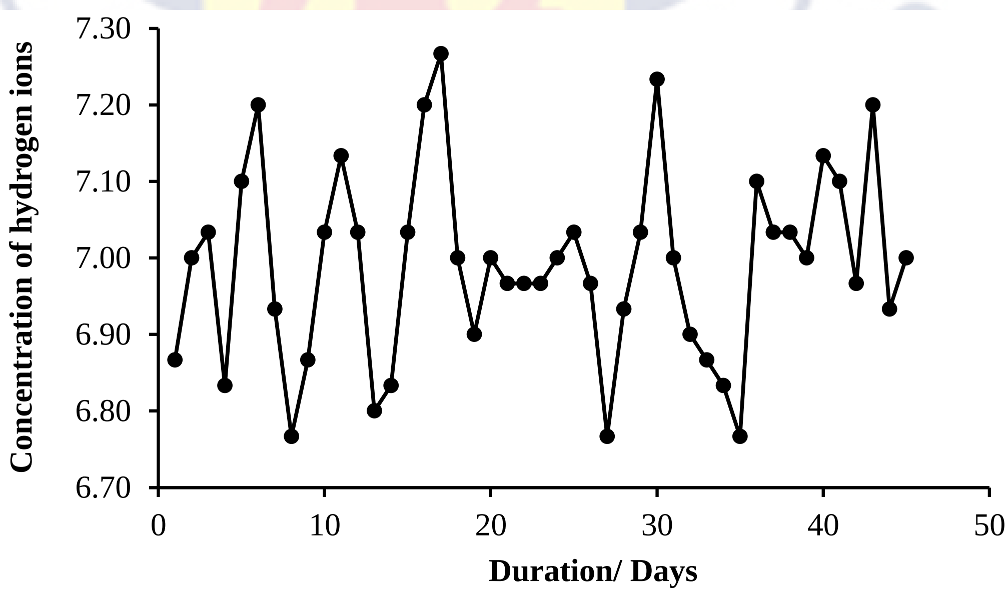


Figure 25: Daily pH readings in the digester containing the water hyacinth

pH readings were taken in triplicates each day for 45 days. At the beginning of the experiment, the digester was operating in a slightly acidic medium. The overall mean pH of the digester was approximately 7.00 which is in the acceptable range for anaerobic digestion.

4.1.5 Utilization of Biogas

The biogas generated was tested for use in homes for cooking burning directly with a burner. The gas was also utilized for electricity generation by using it as a fuel in a generator.

Figure 26: Biogas being utilized to power a generator

The biogas that was produced and stored from this research was used to power a generator. With around 50L of gas, electricity may be created for approximately 10 minutes

Figure 27: Biogas being utilized to power a kitchen stove

When the gas is lighted in the stove, it produces a blueish-yellow colour indicating the presence of a proportion of methane.

4.1.5 Sludge Utilization

From literature (T. Al Seadi et al., 2013; Kathijotes et al., 2015), it is known that the digestate from a biodigester is nutritionally enriched and can be used to augment crop production in agricultural settings. Hence, the produced digestate was applied to several cocoa seedlings placed under the same condition. The growth of these plants was monitored and compared with the plants that the digestate was not applied on.

Figure 28: Digestate being applied on cocoa seedlings as a source of fertilizer

After observing and measuring plant height for several weeks, it was discovered that the plants that received the digestate grew on average taller than the control plants (plants on which fertilizer was not applied).

4.2 DISCUSSION

4.2.1 Composition of Weeds

Thorough understanding of physical and chemical features (e.g., Ash, fixed carbon, volatile solids and moisture content) is needed to be able to utilize weeds such as Water lettuce and Water hyacinth as feedstocks or substrates for the generation of biogas. Physicochemical qualities are critical parameters because they influence the properties of these raw materials during the anaerobic conversion process and output of methane.

The findings of this study as indicated in figure 13 & 14 shows that both Water hyacinth and Water lettuce had high moisture contents, with 92.68% ± 0.05 and 94.11% ± 0.04 being the values obtained respectively. This result is similar but quite higher than the moisture content (93.63 %) of Water lettuce that was obtained by Sinbuathong *et al.* (2020). The values obtained from this study is also comparable to a 94.35 % moisture content that was previously documented for water lettuce by Patil *et a*l. (2011, 2012). Anaerobic digestion (AD) requires an optimal degree of moisture content in order to function properly. A low moisture content of a substrate can have a consequence on the AD process by causing the quantity of glucose-consuming acidogenic bacteria to decrease (Fujishima *et al.*, 2000).

The differences between the current and prior findings could be attributable to a variety of factors including harvesting time and manner, climate, location, pollution, and the kind and duration of storage. The effects of irradiance, nutrients and water availability, temperature, salinity, and compaction are all possible causes.

Ash content of Water Hyacinth and Water Lettuce are 1.56% ± 0.03 and 1.33% ± 0.02 respectively. The results of the ash content test indicate the quantity of inorganic substance that remained after the biomass has been completely consumed. The research conducted by Jimoh et al (2016), yielded higher findings than the results produced by this research. They reported that the ash percentage of the biomasses ranged between 15% and 25%, with the exception of the leaf of the water hyacinth, which had an ash level of less than 15%. Furthermore, the values obtained in this current study are lower than the values found for other biomasses such as Rice husk briquette (16.10%) and Melon shell (19.57%), which were previously investigated. Again, Ayoade *et al*. (1982), and (Rodríguez *et al.*, 2000), reported 30.1% and 21.12% ash contents respectively in their studies. However, the ash content of water melon and cassava peels were 2.85±1.50 and 2.40±0.61 respectively according to the findings of a study by (Igbum *et al.*, 2019). Comparably, it could be seen that ash content of the weeds utilized for biogas production in this study were lower. The reduced ash content of water lettuce and water hyacinth could suggest a lack of mineral availability in the environment (water body). Also worth noting is that, the ash content of substrates has been established to have an inverse relationship with the organic matter content of the substrate. This assertion is backed by a study done by Igbum *et al.*, (2019), where they revealed from their study that maize chaff had the highest percentage of ash but contained the lowest amount of decomposable (organic) matter, whereas water melon had the lowest percentage ash content but contained the most amount of organic matter. High ash content can affect the biogas yield and quality, cause scaling and clogging in digesters and affect the overall efficiency of the conversion process. Therefore, in contrast the low ash content observed from this study indicates that water hyacinth and water lettuce can potentially contribute to higher biogas yields.

Volatile Solids content in the water lettuce and water hyacinth was another characteristic of the plants that was evaluated as part of this study because of the potential impact it could have on the anaerobic digestion process. The actual organic substance available for bacterial action during digestion is the volatile solid

(Bhui *et al.*, 2018; Ganesh *et al.*, 2005; Patil *et al.*, 2011). Following the examination, it was discovered that water hyacinth had 1.12% ± 0.05 and water lettuce had 0.34 ± 0.021 volatile solids respectively. Generally, a sample heated to 600°C in air will burn the organic material, and the weight loss can be ascribed to the sample's high organic content. The Volatile Solid is the material that remains after the heating process is completed. It represents the readily biodegradable organic fraction of the biomass and is a key parameter in anaerobic digestion. Volatile Solids were measured because they are crucial in assessing the biogas potential and the rate of organic matter degradation in biomass. Higher volatile solids content generally indicates a greater availability of organic material for biogas production. However, the lower volatile solids content obtained in this study may indicate that the water hyacinth and water lettuce have a higher proportion of refractory or non-biodegradable organic compounds. This could result in a reduced biogas yield and slower digestion rates.

The proportion of protein content present in the feedstock, which was an important chemical attribute to consider, was also determined. A high protein feedstock may generate an excessive amount of ammonia, which might limit the growth of methanogens during anaerobic digestion. Water lettuce had a protein content of 17.22 ± 0.06 percent, while Water Hyacinth had a protein content of 14.11 ± 0.03 percent. Water lettuce has 20.5% crude protein, according to a study conducted by Banerjee and Mata (1990). Rodrguez *et al*. (2000) did an investigation into the proximate, structural, and mineral content of water lettuce, and discovered a significantly lower amount of protein (8.62%). Ayoade et al.

(1982). found that water lettuce has 13.9 percent crude protein. A 20% protein content was also discovered in the leaves of water hyacinth in a study by (Abdelhamid & Gabr, 1991). However, the study by Moses *et al.,* (2020) is in agreement with the current study having a protein content of water hyacinth of approximately 17%. Protein content is generally related to the environment from which the plant/substrate is being taken from and also the age of the plants. Protein content tends to decrease in ageing plants.(Mako *et al.*, 2011; Men *et al.*, 2006).

In terms of fat/oil content, it was discovered that water hyacinth had a lesser percentage of 0.84% ± 0.00 as opposed to 3.00% ±0.08 water lettuce. Water lettuce has 3.8% crude fat, according to Banerjee and Mata (1990). This value is more similar to the one obtained in this investigation. Moses *et al.*, (2020), also concluded that water hyacinth contains a low-fat content which agrees with the findings of this study. The fat content is thought to influence methane generation. When the amount of fat is high, so does the production of methane. A higher fat/oil content in the biomass indicates a greater availability of lipid rich organic material. Lipids are biodegradable and can be broken down by anaerobic microorganisms to produce biogas. Conversely, a lower fat/oil content suggests that the biomass may have a lower lipid content which could result in a lower potential for biogas production from lipids alone *(Abomohra et al., 2022; Awe et al., 2018; Okoye et al.*, 2002; Park & Li, 2012). This could mean that the methane output seen in this research work was partly due to the fat content of the substrates (water hyacinth and water lettuce).

After the proximate analysis, the fibre contents were found to be 11.52% ± 0.34 for water lettuce and 15.78% ± 0.13 for water hyacinth. The fibre content refers to the percentage of fibrous or structural components present in the sample. It includes cellulose, hemicellulose and lignin, which are complex carbohydrates and contribute to the structural integrity of the plant material. During the A.D process, the breakdown of fibrous components can be a limiting factor. These fibrous materials are more resistant to microbial degradation compared to other organic compounds, such as protein and lipids. Therefore, a higher fibre content in the feedstock may require longer retention times and efficient mixing to complete digestion (Mako *et al*., 2011; Moses *et al.*, 2020b). Conversely, a lower fibre content implies a higher proportion of readily biodegradable organic material, which can potentially lead to higher biogas yields. Rodríguez *et al*. (2000) reported that 19.13 % crude fibre is found in water lettuce. This value was greater than those obtained for this study. Ayoade et al. (1982) again reported that, water lettuce has 19.1% crude fibre. The examination of the fibre contents of water hyacinth and water lettuce contributes to understanding the compositional characteristics of these weeds and guides the optimization of the anaerobic digestion process.

In relation to the elemental constituents, carbon was the highest with a mean value of 22.17% ± 0.12. The Nitrogen, Phosphorus and Potassium were below 4%. The Calcium and Magnesium were below 3% in each of the plants. Rodríguez *et al.* (2000) reported that a 1.32% total Nitrogen was found in water lettuce. Also, according to Gunnarsson & Petersen, (2007), Water hyacinth contains high Nitrogen content which is contrary to the value obtained in this study. According to Chynoweth et al. (2001) and Matsumura (2002), the composition of elements for water hyacinth were found to be; Carbon (38.4%), Hydrogen (5.85%), Oxygen (28.1%), Nitrogen (2.9%), Sulphur (0.47%), Phosphorous (0.77%), Potassium (2.78%), Calcium (1.32%) and Sodium (1.44%). The study by Rodríguez et al. (2000), directly agrees with this study. There could be several reasons for recording low nitrogen content in this study such as variability in biomass. These weeds can exhibit variability in their nutrient composition depending on factors such as its growth stage, environmental conditions, and the specific location form which the samples were collected. Low potassium and phosphorus concentrations were seen in this study. Comparable values were obtained from (Abdel-sabour, 2010).

Macronutrients are recognized to play crucial roles in anaerobic digestion. For instance, Potassium increases the permeability of the cell membrane of the substrates and it is also utilized by methanogens in the course of the digestion process (Masto *et al.*, 2020; Wu *et al.*, 2016). When the substrates are being degraded in the digester, the carbon stored in the substrate is utilized for energy while microbes also utilize nitrogen for growth. This nutrients make available the building blocks for the formation of compounds such as nucleic acids, amino acids and proteins (Neubeck *et al.*, 2017; (Xie *et al.*, 2016). Moreover, during digestion, nitrogen is converted to ammonia, which at low quantities act as a neutralizing agent for sustaining the pH critical for microbial cell growth although can be deadly at greater concentrations. Successful Anaerobic Digestion requires the activation of the microbial community, and this activity is influenced by the availability of specific nutrients. Water lettuce and Water hyacinth are therefore promising feedstocks for Anaerobic Digestion (AD) because of the availability of these macro- and micronutrients.

The Carbon to Nitrogen (C-N) ratio of the feedstock is a significant component that determines the gas production process. The carbon-to-nitrogen ratio in organic matter refers to the amount of carbon present in relation to the amount of nitrogen. For Water hyacinth and water lettuce, the C/N ratios found were 9.82 ± 0.05 and 7.61 ± 0.05, respectively. Most often, organic matter contains more carbon as compared to nitrogen (Flavel & Murphy, 2006). The ratio of carbon to nitrogen is commonly expressed as C: N and is a single integer. As a result, the ratio calculated for water hyacinth suggests that there are 9.82 g of carbon in that organic matter for every 1 g of nitrogen. In addition, the organic matter of water lettuce contains 7.6g of carbon for every 1g of nitrogen. When the C:N ratio of an organic substrate is between 1 and 15, fast mineralization and Nitrogen release occurs, making Nitrogen accessible for bacteria growth (Watson *et al.*, 2002). Microbial immobilization occurs when the C:N ratio exceeds 35. A ratio of 20–30 results in a state of equilibrium between mineralization and immobilization. Generally, a ratio of 20:32 has been proven to be necessary for the synthesis of methane devoid of ammonia inhibition (Leung & Wang, 2016; Pottipati *et al.*, 2021; Smith *et al.*, 2013; Velásquez Piñas *et al.*, 2018; Yang *et al.*, 2019; Yen & Brune, 2007; Zeshan *et al.*, 2012). However, ratios of C/N are sometimes significantly lower or greater than this, therefore it is necessary to employ co-digestion to augment the C-N ratio (Wang *et al.*, 2017; Zhang & Chen, 2016). The value in the current investigation was seen to be lower than the recommended range. Kumar *et al.,* (2010), stated that with a C/N ratio of 19.6 of green waste, anaerobic was efficient. Also, in their study, Mathew *et al.*, (2015), obtained a Carbon-Nitrogen ratio of water hyacinth to be approximately 29.23. The current findings are quite lower as compared to studies conducted by Gunnarsson & Peterson, (2007), who discovered a carbon-nitrogen ratio of 15. In spite of the enormous importance of C/N ratio, it is not the sole component that is necessary for methane generation in substrates. This can be substantiated by a study by Jayaweera *et al.,* (2007), who compared the biogas yield of water hyacinth that was grown under varied nitrogen levels, and discovered that the carbon-nitrogen ratio does not necessarily have to be in the optimal range of 20-30 for anaerobic digestion to occur and methane generated.

Water hyacinth had an estimated Organic Matter content of 38.23 ± 0.21, while water lettuce had an estimated Organic Matter level of 36.12 ± 0.12. The organic component decomposed to CH_4 and CO_2 is primarily responsible for biogas production from the weeds. This result is in agreement with the a study done by Cong *et al*., (2022) who had an organic matter content of water lettuce to be 38 %. A higher organic matter content in the feedstock indicates the greater potential for biogas production. Therefore, water hyacinth and water lettuce with their estimated organic matter content suggests that they are suitable feedstock for biogas production, though water lettuce may have slightly lower biodegradable material compared to water hyacinth.

The computed N-free extract for water hyacinth was 67.94 ±0.010, and the calculated N-free extract for water lettuce was 66.69 ± 0.032. The Nitrogen-Free

Extract is a representation of non-structural carbohydrates such as starches and sugars, and it is free of nitrogen. A higher N-free extract value indicates a larger portion of readily available carbohydrates in the feedstock. From other studies, water lettuce contains 39.6% nitrogen-free extract (Banerjee and Mata 1990, cited by Nuamah, 2017). Rufchaei *et al.*, (2022) also documented a 49.9 % of NFE in water hyacinth. There disparities in values obtained could be due to environmental differences.

In conclusion, because the physicochemical characteristics of feedstocks are heavily influenced by the environment in which they grow, the disparity and inconsistencies between values obtained and values from literature could be attributed to geographical and environmental factors. Thus, the sample site and the environmental conditions in the water bodies where the study species were collected.

Furthermore, the possible influence of trace elements on anaerobic digestion depends on environmental conditions, their content in the substrates, and bioavailability and activity of microorganisms. Therefore, it is crucial to find a substrate/supplement which will contain trace elements in a form accessible to microorganisms.

4.2.2 Biogas Yield of Water Lettuce and Water Hyacinth

From the results obtained, as shown in figure 15, 16 and 17, it can be said that on the average, Water hyacinth produced about 2.58 L of biogas per day and a cumulated biogas yield of 116.20 L. Water lettuce on the other hand yielded an average of 1.56 L of gas daily and at the end of 45days digestion period, produced a cumulative volume of 70.40L. The higher biogas yield from water hyacinth is likely influenced by its higher organic matter content as well as its higher nitrogrn content compared to water lettuce. These factors contribute to better microbial activity and more efficient biogas production during anaerobic digestion.

The present study's findings are consistent with prior findings achieved employing Water hyacinth as a feedstock, which is encouraging (Soeprijanto *et al.*, 2020b). With different quantities of water, Patil *et al.*, (2012), executed anaerobic digestion of water hyacinth at mesophilic temperature range for 60 days and realized that the highest biogas yield of 0.36l/g VS was obtained. Rozy *et al.*, (2017), also reported that under optimal condition for 40 days, Water hyacinth had a biogas output of 0.398 l/g VS. Furthermore, O'Sullivan *et al.*, (2010), discovered that Water hyacinth has a biogas generation capacity of 0.2–0.4 l/g VS. Vaidyanathan *et al.*, (1985) and Mathew et al. (2014) reported biogas yields of 0.430 l/g VS and 0.552 l/g VS respectively from the same plant. Additionally, when water hyacinth was coupled with lemon industrial effluent in an anaerobic digester, a maximum biogas production of 0.87 l/g TS was attained in 16 days (Navarro *et al.*, 2012). The majority of the prior results described above were acquired in batch cultures with a different inoculum each time they were performed. The current investigation, on the other hand, was conducted in a continuous mode. As a result, the organisms were expected to be more active in the continuous mode than they were in the batch mode.

From the biogas production findings in figure 17, an observation that can be noted is that, for both substrates, gas output began slowly but increased with duration in the digester. There was little sign of gas production in the two bio-digesters during the first four days. This could be because the inoculums are in a lag phase or that the methanogens are experiencing metamorphic development by assimilating methane precursors created by the preliminary activity as suggested by (Bal & Dhagat, 2001). It is widely accepted that Volatile Fatty Acids are produced during the early phases of the entire biogas generation process, resulting in a decrease in pH and a reduction in the development of methanogenic bacteria and methanogens(Bauer *et al*., 2008; Campanaro *et al.*, 2016; Guo *et al.*, 2019). In other words, the bacteria are rendered inactive due to low pH.

From day 31 to day 45, it was found that gas production began to become more consistent. A constant gas generation each day Signifies that the procedure had attained steady-state conditions in continuous mode (Soeprijanto *et al.*, 2020b)

Readings of the volume of biogas produced were reported to have reduced on some days for each bio-digester. This could be related to the considerable rain that fell on those days, resulting in cold temperatures. A relationship between temperature and gas production has been established (Cao *et al.*, 2020; Ramaraj & Unpaprom, 2016). Cold temperatures can negatively impact the anaerobic microorganisms responsible for biogas production. The A.D process is more efficient at warmer temperatures. Conversely, cold temperatures can slow down microbial activity leading to reduced gas production.

The gas yield was considerably increased by utilizing a water hyacinth mixture in conjunction with an inoculant (cow dung). This is because both (weeds+ inoculum) can have complementary nutrient profiles. Water hyacinth/ Water lettuce are rich in organic matter while cow dung is a good source of nitrogen and other essential nutrients. The combination of these feedstocks provides a balanced and nutrient rich substrate for anaerobes, promoting their growth and activity (Abdeshahian *et al.*, 2016; Monteiro *et al.*, 2011). The combination of water lettuce/water hyacinth and cow dung could have significantly increased the sources of carbon and nutrients needed by microorganisms in order to degrade the weeds and subsequently produce biogas.

4.2.3 Biogas Composition

On a daily basis, the components of the gas produced by the fermentation of weeds were identified and analysed for their composition. When the substrate was first introduced into the biodigester, significant carbon dioxide concentrations were observed, with very little methane present. Additionally, the levels of nitrogen and oxygen gases were extremely high during the first few days, but they steadily decreased as the days progressed.

Of the total biogases produced Over the 45-day period, methane gas had an overall mean of 53.63% ± 2.84 for water lettuce feedstock as shown in figures 18 and 19. Also, from figure 20 and 21, a mean value of 55.23% ± 7.32 methane gas was recorded for water hyacinth as feedstock. Carbon dioxide was the second highest component contained in the produced biogas with a mean value of 23.67

± 4.66 for water lettuce and18.5% ± 3.36 for Hyacinth. Also, for both feedstocks, thus from figure 19 and 21, the percentage of hydrogen sulphide and carbon monoxide in the biogas was very low with both recording a mean value of 0.00 ± 0. Nitrogen gas and oxygen gas were also given out during the anaerobic digestion process and recorded mean values of 16.10 ± 2.10 and 6.60 ±1.04 respectively for water lettuce. Water hyacinth also had 18.4% ± 6.42 Nitrogen gas and 7.9% ± 1.42 Oxygen gas.

The results of this study were compared with other research findings and it was discovered that *Lemna minor* (common duckweed) produced a maximum methane yield of 41 percent after being digested for 32 days (Ström, 2010). In addition, Eichhornia crassipes (water hyacinth) produced a 62 % methane content after 60 days of retention time (Mathew *et al.*, 2015). In an investigation on Salvinia (water moss), it was discovered that the plant generated 63% of the CH_4 over a 60-day digestive period (Mathew *et al.*, 2015). Also, Pantawong et al. (2015) found that a 45-day anaerobic digestion of *Pistia stratiotes* produced 66.35 % methane gas, which they attributed to the bacteria population. In accordance with the findings of Jonsson *et al.*, (2003), biogas from sewage typically contains from 55 to 65 % methane, 35 to 45 percent carbon dioxide, and less than one-tenth nitrogen. Elaiyaraju & Partha, (2012), concluded from their study that the released biogas was evaluated and found to include approximately 65 - 70% methane and the remaining 20-25 % carbon dioxide.

Depending on the pre/post treatments employed, biogas yields could differ. When Patil *et. al*., (2011) conducted their research, they used the entire water hyacinth biomass (leaf, stem, and root) which were sun dried and then dried in the oven at 60°C for six hours before being administered to the digesters. Acetic acid was also utilized exogenously to increase gas production, according to *Mathew et al* (2015). In this study however, anaerobic digestion parameters such as pH were not maintained by the use of chemicals such as carbonate. Also, although the entire biomass of the feedstocks was used in the digestion process, they were not sun or oven dried but rather pounded. The methane yield was also found to be relatively similar to some of the literature cited above. Also, the percentage of CH_4 can vary depending on the location of the source of feedstocks.

According to the findings, the amount of nitrogen gas was significantly higher than those found by other researchers. Proteins, amino acids, and urea are the primary forms of nitrogen that enter the anaerobic digestion process (Angelidaki & Ahring, 1993; Fang *et al.*, 1994; Yokoyama *et al.*, 2007). Higher nitrogen concentrations in anaerobic digestion systems have been shown to have a deleterious influence on a variety of processes, as detailed by Calli *et al.*, (2006) and Molaey *et al.*, (2018). It can have effect on microbial growth and development. *Methanpretoarchaea* as compared to other bacteria, has exhibited much more sensitivity toward ammonia stress (Fricke *et al.*, 2006; Hansen *et al.*, 1998; Heinrichs *et al.*, 1990; Sawayama *et al.*, 2004).

During the production of biogas under anaerobic conditions, hydrogen sulphide and other sulphide compounds are produced by a variety of distinct pathways (Ramaraj & Dussadee, 2015; Rasi *et al.*, 2007). The values obtained for hydrogen sulphide component of the gas generated in this study was relatively negligible. This can be ascribed to the fact that a de-sulphuriser was attached to the digester.

As reported by Ofori-Boateng & Kwofie, (2009b) and Rasi *et al.*, (2007), the most significant contaminants in biogas is hydrogen sulphide and its oxidation products.

The breakdown of sulphur-containing amino acids (such as those found in manure, for example) and the anaerobic methylation of sulphide are examples of reactions that result in the formation of methanethiol and dimethyl Sulphide (DMS When the concentration of these contaminants exceeds 50ppm, corrosion begins. Most metals react with hydrogen sulphide, which is a gas (Persson et al. 2006). In cases where hydrogen sulphide concentration is high, biogas upgrading must be performed.

It must also be noted that when substrates are primarily composed of high molecular compounds (cellulose and hemicellulose) and carbohydrates, methane generation tends to be quite limited.

4.2.4 Other Factors That May Have Affected the Gas Production

The quantity of biogas generated as a function of the quantity of raw material input will vary depending on a number of factors, including the quality of the organic matter and the ambient parameters. The temperature and pH of the surrounding environment have an impact on the intensity of microbial activity, which is necessary for methane synthesis.

4.2.4.1 Power of Hydrogen (pH)

pH is said to be crucial to digester health. The contents of the digester were monitored for their alkalinity or acidity.

In this study, it was realized that pH values fluctuated within the range of 6.5 to 7.5 across the digestion period. These values are in the optimum pH range allowed during anaerobic digestion. These helps to give stability to the process and prevent dominance of undesirable microorganisms. Also, the values obtained shows indicates a reasonable buffering capacity of the digester. In a study by

O'Sullivan *et al.*, (2010), he realized that appreciable biogas yields with 50% methane content were generated when the pH of the digesters were maintained at a range of 7-8.

4.2.4.2 Temperature

In the case of this study, the anaerobic digestion performed was done under mesophilic temperature ranges. Thus, from around 25 degrees Celsius to about 37 degrees Celsius. From the graphs (figures 22 and 23) it could be seen that the temperature at the initial stages of the process was lower. Also, slight temperature fluctuations were observed over the digestion period. These observations could be attributed to temperature changes in the environment. Thus, either sunny or rainy days. The digester was placed outside hence the temperature was dictated by the temperature of the environment. Also, even though the temperature was low at the beginning of the process, the opaque nature of the digester made it possible for heat to be trapped in it and hence the steady increase in temperature. From literature, Cao *et al.*, (2020), it has been established that temperature and substrate type are the most critical elements influencing the performance and stability of the anaerobic digestion process. When these elements work in conjunction, their impact is felt on the metabolic conversion pathways, the structure of the microbial population, the kinetics and thermodynamic balance of the biochemical reactions and the stoichiometry of the products formed. It was therefore to conduct a daily monitoring of temperature changes in the digester, since it affects the production of methane.

4.2.4.3 Pretreatment

Another factor that could possibly have influence the anaerobic digestion process was the kind of treatment given to the weeds before being charged into the digester. The gas output seen in this study could be partly attributed to the pretreatment. Pounding the weeds reduced the size of the weeds increasing their surface area for microbes to easily degrade. Studies have been conducted to substantiate this claim. For example, the study by Moorhead & Nordstedt, (1993), studied the "influence of comminution particle size, nitrogen concentration and inoculum size on the anaerobic fermentation of the water hyacinth" and concluded that when the crushed particle size was reduced to 6.04 mm, the amount of biogas and methane generated by water hyacinth was greater.

4.2.5 The Viability and Suitability of Water Lettuce and Water Hyacinth as Feedstocks for Biogas Production

The suitability of Water lettuce and water Hyacinth obtained from the Volta Lake as substrates for methane and biogas generation was also looked at in this study. From the results obtained, it was discovered that both invasive weeds can be digested by microorganisms, resulting in the production of biogas under anaerobic conditions for a length of time. Furthermore, it was discovered through chemical composition analysis that the chemical and physical characteristics of these plants make them a feasible feedstock for biogas production. Water hyacinth and water lettuce are examples of waterweeds that have become a nuisance to the environment, irrigation systems, and agriculture. Both plants were discovered to have cellulose, nitrogen, necessary nutrients, and high fermentation levels that can be used to produce biogas. Carbon and nitrogen were discovered to be present in the plants.

To buttress the observations made in this current study, it was necessary to compare the results with some other investigations that have been conducted on biogas production using AD techniques on lignocellulose biomasses. Malik (2006), observed from his study that although water hyacinth can be used to generate biogas, the liquid anaerobic digestion process must be used due to the fact that the plant contains about 95% moisture content and low Total Solids content. The effective conversion of organic matter into biogas is what an anaerobic digestion is grounded on. Comparing these weeds and their ability to be converted to biogas to other renewable sources of energy such as windmills, solar cells etc., it could be realized that the use of these weeds are advantageous in terms of production and investment cost (Rao *et al.*, 2010). According to Mathew et al. (2014), E. crassipes may be quickly hydrolysed to sugar due to its hemicellulose and cellulose properties as well as its low lignin level. O'Sullivan *et al.,* (2010), recorded appreciably (0.2-0.4 L/g VS) biogas output when they studied the potential of water hyacinth for biogas generation. An even greater biogas yield of 0.430 L/g VS was recorded in a study by Vaidyanathan *et al.*, (1985), who anaerobically digested water hyacinth in batch mode.

These weeds that are currently invading water bodies including the Volta River, are either being eliminated with either biological agents or herbicides and left to decompose or taken out for disposal in landfill at high cost. The trials undertaken in this paper further goes to reveal that these two invasive weeds may be easily decomposed under anaerobic conditions to produce considerable amounts of biogas. This can help save the expense used in the chemical control of these weeds.

Of the many merits, the availability of significant amounts of these weeds for use as feedstocks is one of them. Furthermore, no competition exists between these weeds and land plants utilized in crop farming. Again, the harvesting and transportation of these weeds can be done manually on a scale and does not require the introduction of new harvesting technique. It grows quickly and requires no seedling, weeding or fertilizing, thus, its free.

4.2.6 Ideal Weed to Use as Substrate for Biogas Generation in terms of Commercialization.

Grounded on the results generated from the Analysis of variance, and the Z-Test, which were performed at a 95 % confidence level, it was discovered that the p-values were lower than the confidence interval (0.05), and that the critical values were lower than the test results. When the calculated value is greater than the critical value, it indicates that the test score is in the rejection zone (failing to accept the null hypothesis) which is the case. The converse is true: if the test result is less than the Critical Value, it indicates that the test score is in the Acceptance Zone, and we are therefore unable to reject the null Hypothesis.

It can be seen from Table 4 and 5 that the test score (calculated z and F-values) were higher than the critical values. This simply indicates that the volume of biogas generated by each plant is statistically dissimilar. As a result, the null hypothesis is ruled out. Also, from the same tables, the p-values obtained were lower than 0.05 which means that 95% of the time, the biogas output from the two weeds were statistically different. It also means that there is a 95 % probability that the observed differences in gas yields were not due to random chance but represent true differences between the plants. Hence the null hypothesis which states that there is no difference in the biogas yield of water lettuce and water hyacinth from the volta estuary, can be rejected. Based on this assumption, it is possible to provide recommendations on which weed would yield out more biogas when employed on a commercial setting. Conclusion can be made from the tests performed that water hyacinth is the ideal weed to use as a biogas feedstock because it produces higher biogas yields, methane yields, and hence higher income levels than other weeds.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the findings of the study, draws conclusions, and gives recommendations for policy. Future research directions are also proposed, which are informed by an expanded complete and in-depth understanding of the biogas and anaerobic digestion processes.

5.1 SUMMARY

Water lettuce and Water Hyacinth, two invasive plants, were investigated in this research to determine whether or not they were suitable as substrates for biogas production. The points given below provide a summary of the entire thesis, including the methodologies used and the outcomes attained, in just a few sentences.

1. The invasive weeds (Water Lettuce and Water Hyacinth) were sampled from the Volta River Estuary at Ada in Ghana.
2. The Chemical composition analysis was performed on both plants.
3. A $1m^{3-}$by $1m^3$ portable anaerobic biogas digester was set up by using Cow dung as a source of inoculum
4. Before charging the biodigesters, the feedstocks (Water hyacinth and water lettuce) were pre-treated by pounding them with a pestle and mortar
5. Daily and Cumulative gas yield and gas composition measurements were done.
6. The results obtained showed that, both weeds produced appreciable gas and methane yields. However, Water Hyacinth recorded the highest gas yield and highest methane composition
7. Both weeds have been deemed as viable and suitable feedstocks for biogas production
8. Water hyacinth was therefore proposed as the better option to use as a feedstock in commercial biogas production.

5.2 CONCLUSION

The current research explored the possibility for biogas to be generated from aquatic weeds such as Water hyacinth and water lettuce. It was discovered that both weeds had the capability to generate methane (CH_4) when anaerobically digested in the presence of an inoculum. The anaerobic digestion was achieved within the mesophilic temperature range. Comparing both weeds, Water Hyacinth appears to be a more viable substrate for biogas production. It is possible that the decreased biogas yield obtained from water lettuce is related to the plant's reduced biodegradability. It has been seen that the biogas produced has the ability to generate power. The digestate was also assessed to have applicability in the agricultural sector as a fertilizer substitute.

After considering the evidence provided by this study, it can be concluded that these invasive plants represent a promising biomass source for biogas production. Biogas will play a significant role in the future since it may be used to generate electricity from renewable sources.

Also, it is crucial to continuously optimize the anaerobic digestion process in order to increase biogas output when these weeds are utilized as feedstocks.

5.3 RECOMMENDATIONS

The following recommendations have been propounded in light of the findings of this investigation.

1. Further investigation should be conducted into the techno-economics of successfully converting these weeds into biogas using anaerobic digestion. Thus, to know if the process is economical and scalable.

2. Anaerobic digestion research focusses mostly on methanogenesis, which is driven by the microbial communities that inhabit the environment. As a result, future research should be focused on gaining a better knowledge of the bacterial ecology.
3. Additional research should be conducted in Ghanaian waters to assess the suitability of using seaweeds such as sargassum as feedstocks for biogas production. This could help curb the recent surge in sargassum populations on Ghanaian beaches.
4. The search for alternative energy sources such as biogas should be intensified so that ecological disasters like deforestation, desertification, and erosion can be arrested in our rural areas.

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