Original Research Article

ASSESSMENT OF ECO-ENVIRONMENTAL IMPACT OF HARVESTING GREENHOUSE GAS FROM BIO-WASTE: A CASE OF WASTEWATER TREATMENT PLANT

ABSTRACT

AIM: To determine economic and environmental impacts of greenhouse gas harvesting from bio-waste generated at waste water treatment plant**.**

STUDY DESIGN: Quantitative experimental research for anaerobic digestion using a prototype biodigester.

PLACE AND DURATION OF STUDY: Case study of Kaunda square wastewater treatment plant in Lusaka city of Zambia. The duration of study was one year inclusive of research proposal writing.

METHODOLOGY: Two Anaerobic Digestion (AD) experiments were conducted, along-side was control experiment-c. The first experiment-a used a balloon as means of biogas collection while experiment-b used water displacement technique. Each experiment used 9.6kg feedstock (on dry basis) into a 40 litres prototype biodigester and subjected to AD for 30days hydraulic retention time (HRT).

RESULTS: Total biomass potential available as feedstock at kaunda square wastewater treatment ponds was found to be 483,947kg per annum. The 9.6kg biomass feedstock used in experiments A and B produced 0.0179M^3 and 0.0165M^3 of biogas respectively leading to 0.0172M^3 as average monthly biogas production. Scaling-up these experimental findings of using 9.6kg feedstock to produce 0.0172M^3 biogas, resulted in Kaunda square wastewater treatment plant with feedstock potential of 483,947kg yielding 868.43Kg (755,156.78 liters) of biogas production per annum.

Total amount of greenhouse gases (GHGs) of environmental importance came from the summation of contributions of methane and carbon dioxide and expressed as carbon-dioxide equivalents$(CO_{2\,Eq})$. The value of the two GHGs was found to be $12{,}114.61KgCO_{2Eq}$ with direct effect on global warming and climate change while the digestate had its economic value in agricultural use where the potential stood at 9,662 by 50kg bags of nitrogen/sulphur rich organic fertilizer per annum.

CONCLUSION: Energy harvesting through harvesting of greenhouse gases from bio-waste can lead to reduction in emission of greenhouse gases, reduce energy deficit and improve food security through soil preservation.

Keywords: Bio-waste, Greenhouse Gas Emission, Energy Harvesting, Economic Benefit, Environmental Impacts, Wastewater.

1. INTRODUCTION

Greenhouse gases (GHGs) are gases in the earth's atmosphere that trap heat [1]. Greenhouse gases usually occur naturally for our survival but anthropogenic activities have led to their notable increase in the atmosphere. The situation of increased atmospheric GHGs leads to global warming and Climate Change. Some of the already felt impacts of global warming and climate change are extreme weather events such as droughts, floods and heat waves among others.

The search for clean and green alternative energy sources led researchers to focus on renewables. Unlike fossil fuels that emit harmful GHGs and take millions of years to form, renewable energy sources or rather renewables are plentiful and constantly being replenished all around us [2]. Some examples of renewables include; Geothermal energy, Bioenergy, Wind energy and Solar Photovoltaics to mention a few.

The literature survey pointed to the generation of sludge (bio-waste) at a wastewater treatment plant and also the impacts of not harvesting biogas as well as the economic and environmental benefits of digestate. To achieve this, a study was conducted at Kaunda Square Sewage Treatment Plant located within Lusaka City of the Republic of Zambia.

The scope of the study was to determine the biomass potential at a wastewater treatment plant, to assess the economic benefits and environmental impacts of harvesting greenhouse gases produced from the bio-waste in question using anaerobic digestion. Therefore, the study sought to provide solutions to not only the existing challenges faced by water utility companies in managing their bio-waste but also to reduce emission of greenhouse gases into the atmosphere.

2. MATERIALS AND METHODS

The methodology of the study involved various tasks that were all aimed at studying on how biogas can be produced and harvested from the wastewater (sewage) treatment processes, and then assessing results for economic and environmental benefits. Therefore, the experimental design of study involved the following activities; desktop review of existing data, setting up of a drum-biodigester, determination of biomass resource potential, economic power potential (EPP) as well as assessing the positive impact of harvesting GHGs from wastewater treatment plants.

2.1 Materials

The materials, equipment and tools used in this study included; a 40 litres metallic drum batch-biodigester, balloons used as a biogas collection chamber, a displaced water collection bottle, 1.5 metres long biogas conduit pipe, pick and shovel for digging biodigester hole. Other materials and tools included; a string, ruler and a laboratory measuring cylinder for quantifying the produced biogas, a plastic sack for collection bio-waste as well as a container that was used for drawing water to use for experiments.

2.2. Method

The methodology involved the collection of both primary and secondary data that were relevant and specific to the topic of study.

2.2.1. Primary Data: Primary data was essentially collected from the anaerobic digestion processes which involved subjecting a specific amount of bio-waste to anaerobic biochemical processes that led to production of biogas. It is this produced biogas leaving the bio- digester which was later broken down into its percentage composition of; methane (CH_4 ; 65%), carbon dioxide (CO_2 ; 30%), hydrogen sulphide (H_2S ; 2%) as well as trace of other gases such as oxygen (O_2) and nitrogen (N_2) which composes the remaining 3% [3]. Of these biogas constituents, Methane and Carbon-dioxide are key Greenhouse Gases (GHGs) that were harvested in this study. Therefore, the assessment of economic benefits and environmental impact of harvesting biogas from wastewater treatment ponds were based on these GHGs.

Procedure: Two anaerobic digestion (AD) experiments A and B were conducted with third experiment C being a control in both experiments. Experiment-A used a balloon as direct means of biogas collection while Experiment-B used a water displacement technique to measure amount of biogas that was produced. The two experiments each had a 9.6kg (on dry basis) of co-digested bio-waste that was inoculated into a 40 litres prototype batch reactor (drum bio-digester) with a valve for biogas outlet into a balloon whose maximum capacity was to unknown since measurement of produced biogas was done instanteneously by opening the gate valve. The bio-digester was then slowly filled with tap water to a 35 litres mark. This gave the total feeding level of 0.035M^3 (27.4% bio-waste) while the free space left for gas production was 0.005M^3. The HRT of a mesophilic reactor is 14–40 days while it is 14–20 days for a thermophilic reactor [4]. This study was conducted in October 0f 2023 when temperatures reached as high as 39℃ which dictated the experiments to be mesophilic. As such, an average of 30 days was considered to be the hydraulic retention time (HRT).

Figure 1 below shows the configuration of the AD experiments.

***Fig 1**. Shows a Metallic Drum Bio digester and a balloon as biogas collection chamber*

2.2.2. Secondary Data: The secondary data was obtained from existing desktop data and information at place of study. Literature review of various scholars was also carried out that led to gaining of sound knowledge about how biogas is produced and also identification of the gap which needed carrying out of a research in order to find solutions to the identified problem.

A. *Desktop Data Review*

The review of desktop data was done by reviewing existing Booklets, data recoding Books, Registers and also from information tags attached to equipment at the case study, called Kaunda Square Wastewater Treatment Ponds, in Lusaka City of Lusaka Province in the Republic of Zambia. Some of the data collected from study area included; average sewer influent flow rate (95Litres/second), approximate amount of eutroweed (weed that grow due to eutrophication) generated per annum (400Tonnes/year) and average amount of sludge generation (65Tonnes/year which in this study came out to be 77.9Tonnes/year).

B. *Literature Survey*

The literature relevant to the study were based on; the stages involved in wastewater treatment leading to generation of bio-waste feedstock, biochemical processes involved in biogas production, design parameters of a biodigester and also bordered on issues of environmental importance.

a. Stages of Wastewater Treatment

According to [5], the water entering a wastewater treatment plant (WWTP) undergoes a series of physical, chemical and biological processes in order to remove the pollutants it contains. The study focused on the secondary stage since it is responsible for production of sludge (bio-waste) that was used as feedstock in the experiments. Figure 2 below shows the Schematic diagram of conventional wastewater treatment process up to sludge disposal.

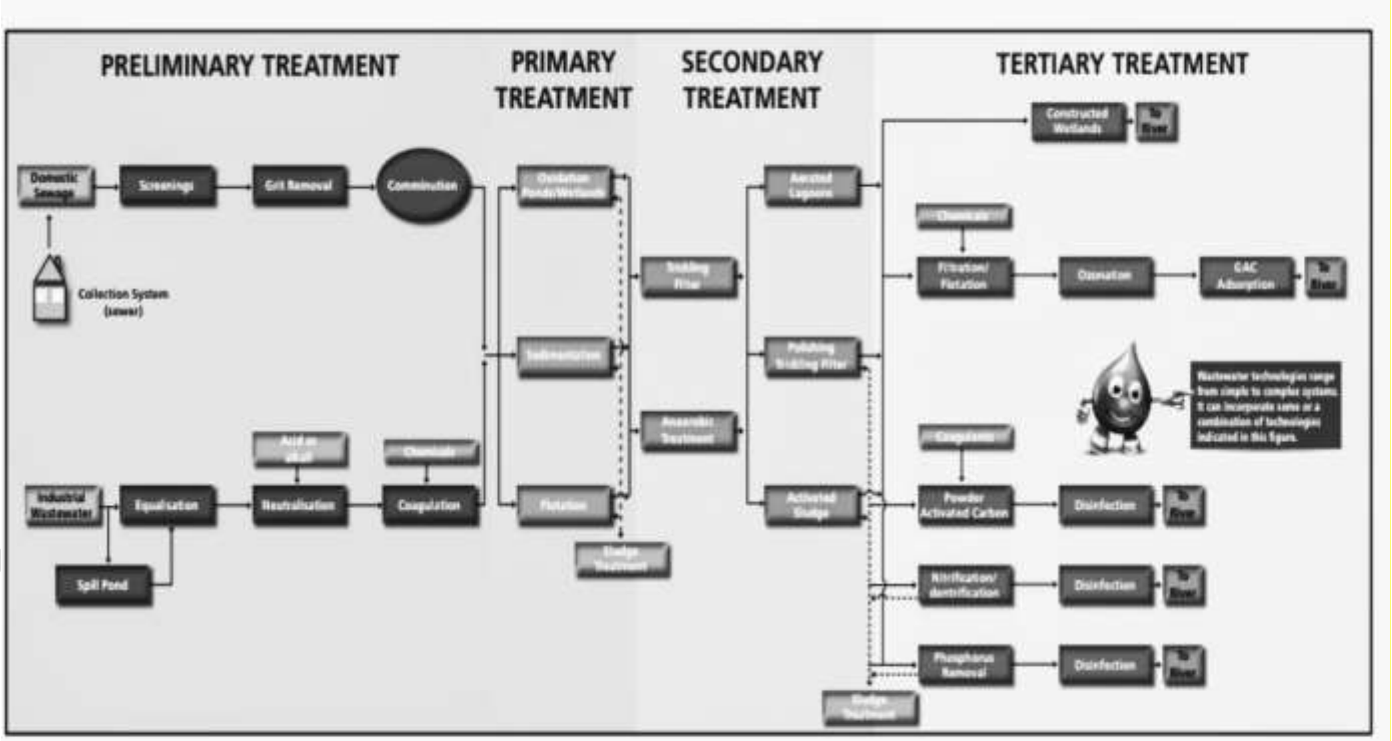

Figure 2: Schematic diagram of conventional wastewater treatment process leading to sludge generation (Source: Water Research Commission, 2015. [**6**]).

b. Anaerobic digestion

The anaerobic digestion (AD) is defined as the decomposition of sewage or other organic waste material by anaerobic microorganisms, typically used as a means of waste disposal or energy production [7]. The AD process produces biogas through decomposition of organic materials under anoxic conditions (in absence of oxygen supply). Biogas actually provides significant advantages over other forms of bioenergy because AD is an energy-efficient and environmentally friendly technology [8].

The AD consists of a series of biochemical reactions where bacteria break down the organic matters of any substrate into a gaseous mixture (CH_4, CO_2, H_2, H_2S, etc.) in the absence of free oxygen [9]. Figure 3 below shows the general steps in the AD process where organic feedstock is first subjected to pre-treatment in order to increase surface area for microbial reaction. Thereafter, the organic feedstock is fed into the digester to generate biogas which can later be purified before it is stored for final usage.

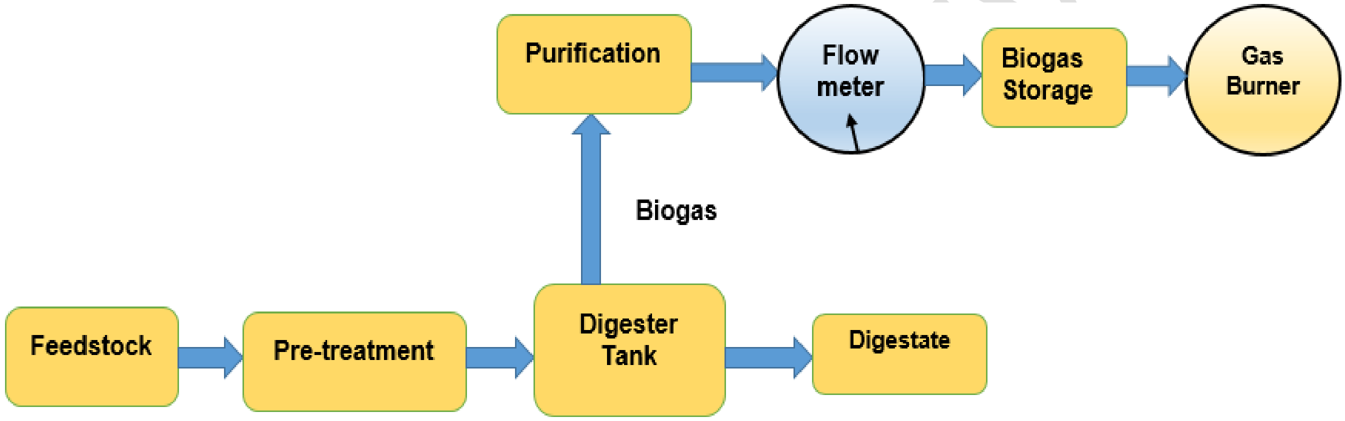

Fig 3 : *General steps in Anaerobic Digestion for Biogas production (Source: Adapted from* **[10])**

In comparison with fossil fuels, AD technology can reduce Greenhouse Gas Emissions (GHG) by utilizing locally available organic resources while the by-product of this technology, called digestate, is a high-value fertilizer for crop cultivation and can replace common mineral fertilizers [11]. [12] also provides that in addition to the first step of AD process called hydrolysis, the consortium of microorganisms that drive AD are divided into two groups namely; ***Acid Producers*** called acidogens and acetogens while the other group are ***Methane Producers*** which are referred to as methanogens as outlined below;

AD was further defined as a biochemical process during which complex organic matter is decomposed in absence of oxygen by various types of anaerobic microorganisms [13]. The process of biogas formation is a result of linked process steps, in which diverse microbial communities collaborate to break down the complex biomass polymers at different stages and turn them into a gaseous mixture [14]. The AD biochemical reactions are divided into four distinct stages namely: i) hydrolysis, ii) acidogenesis, iii) acetogenesis, and iv) methanogenesis [14].

Hydrolysis: This is the first step in anaerobic digestion process that involves enzymes in the transformation of insoluble organic materials and higher molecular mass compounds such as lipids, polyssacharides, proteins, fats and nucleic acids (polymers) into soluble organic materials (monomers) [14].

Acidogenesis: The monomers produced in the hydrolytic phase above are then taken up by different facultative and obligatory anaerobic bacteria and are degraded further into short chain organic acids such as butyric acids, propanoic acids, acetic acids, alcohols, hydrogen and carbon dioxide. In general, during this phase, simple sugars, fatty acids and amino acids are converted into organic acids and alcohols [14].

Acetogenesis: The products produced in the acidogenic phase are now consumed as substrates for the other microorganisms, active in the third phase. In this stage, products which cannot be directly converted to methane by methanogenic bacteria are converted into methanogenic substrates. The volatile fatty acids and alcohols (VFA) are oxidized into methanogenic substrates like acetate, hydrogen and carbon dioxide. The VFA with carbon chains longer than one unit are oxidized into acetate and hydrogen [14].

Methanogenesis: In the methanogenic phase, the production of methane and carbon dioxide from intermediate products is carried out by methanogenic bacterial under strict anaerobic conditions. Methanogenesis is an anaerobic respiration that generates methane as the final product of metabolism. During methanogenesis, H_2 is oxidized to H^+ while CO_2 is reduced to CH_4. Although similar in principle to other types of respiration, methanogenesis has some distinctive features; the energy yield is very low (≤1 ATP per methane generated) since it is chemically bounded in the substrate and remains mainly in the produced biogas in form of methane [14]. Figure 4 below shows the biochemical processes involved in the anaerobic digestion.

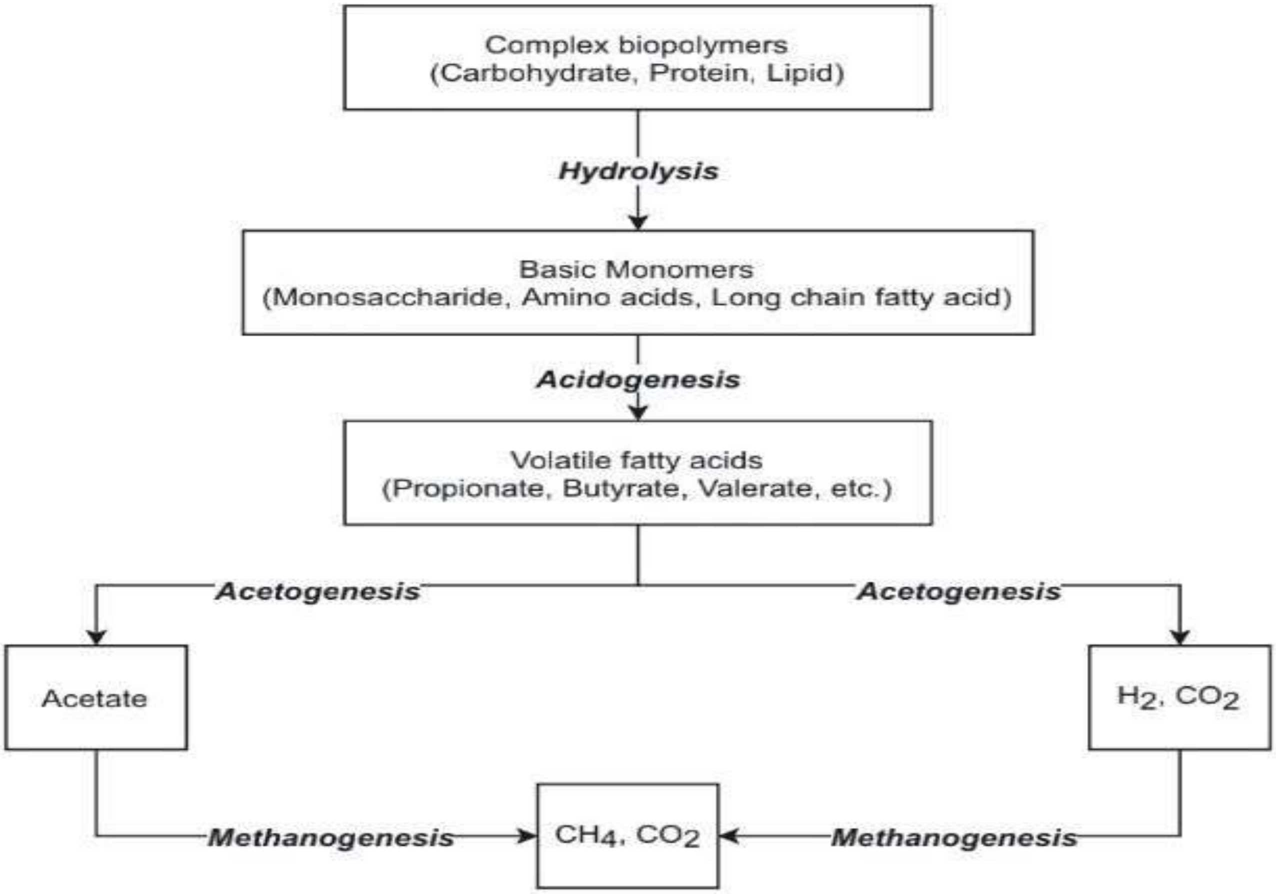

***Figure 4**. AD biomass decomposition stages (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) and key compounds (Curtesy; [14]).*

c. Biodigester variations

The bio-digester or just a digester is a natural system that uses organic agricultural waste or primarily manure to produce biogas (fuel) and biol (natural fertilizer) by means of anaerobic digestion [15]. There are basically three variations of biodigesters namely;

i. *Fixed dome biogas plants*: It has an immovable gas holder and a displacement pit. The upper part of the digester stores the biogas while the waste is displaced in the displacement pit. Pressure increases with an increase in biogas. Figure 5 below shows the unground fixed done biodigester as captured at Manchinchi Sewage Treatment Plant under Lusaka Water and Sanitation Company Limited.

ii. *Floating-drum biogas plants*: It consists of underground bio-digesters and movable gas holders. The gas is collected in the drum above the digester. This moves up and down according to the biogas produced.

iii. *Balloon plants*: Has a rubber bag or balloon and it combines the bio-digester and gas holder. The skin of the rubber bag is connected to the input and output. This study actually used a balloon as means of biogas collection.

The [16] indicated that there are multiple types of biogas digesters available to choose from. These bio-digesters are made of various materials such as concrete, steel, brick or plastic and can be shaped like silos, troughs, basins or ponds and either placed underground or on the surface. AD implementation around the world varies significantly from small-scale household digesters in developing countries to large farm-scale or centralized digesters in developed countries [17]. For the purpose of this study, a small-scale digester was designed out of a recycled 40 litres metallic drum without compromising with existing environmental, economic and technical policies in Zambia.

***Figure 5**. Example of a Fixed dome biogas plant as captured at Manchinchi Sewage Treatment Plant under Lusaka Water and Sanitation Company Limited.*

d. Climate Change

Climate change means a change of climate, which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods [18]. Among the negative impacts caused by anthropogenic activities is the emission into the atmosphere of methane and carbon-dioxide as a result of anaerobic decomposition of sludge at a wastewater treatment plant. These two gases are actually major contributors to global warming and climate change. Therefore, harvesting of methane from bio-waste (sludge) and using it for energy production contributes towards climate control.

2.3. Findings

The findings from the research conducted were about; the quantity of available biomass feedstock at wastewater (sewerage) treatment plant, potential amount of biogas that the said biomass feedstock can produce, and the assessment of economic benefits and environmental impacts of harvesting this biogas.

2.3.1. Biomass Feedstock at WWTP

The Biomass Feedstock (Bio-waste) available at a Wastewater Treatment Plant (WWTP) was initially considered to be composed of four streams namely; sludge, scum, algae and eutroweed as shown in figure 6 below.

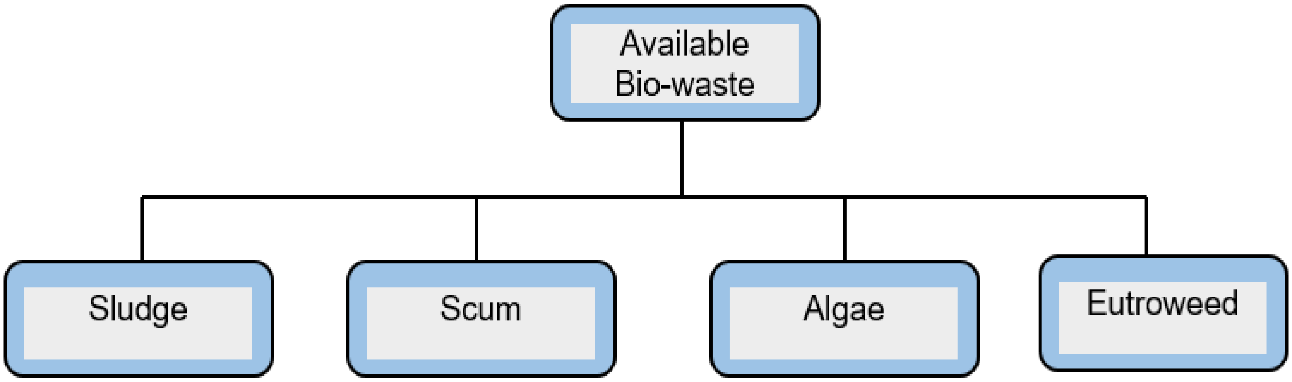

***Figure 6**. Show possible streams of bio-waste from WWTP available as feedstock for Bio digestion*

However, it was discovered during the study that there were only two possible streams of bio-waste. The first stream was collectively called Sludge and was composed of the actual sludge, scum and algae that was separated from wastewater as it underwent the treatment stages. The second stream of bio-waste was called eutroweed, which refers to weeds that rapidly grow on and around the WWTP due to excessive presence of nutrients from the wastewater.

The harvest residue ratio (h) and harvest residue recoverability ratio (hr.) were collected from [19]. In particular, the weed component of the feedstock was taken to be equivalent to the maize stovers (refer to appendix) while the quantity of Sludge was calculated from the influent flow rate (Q) of the wastewater thereby yielding two different values (HR_1 and HR_2) of the feedstock quantity which were later summed up in order to get the total amount of biomass feedstock available at WWTP.

a. Biomass Feedstock from Eutroweed (HR_1)

$$\boldsymbol{HR_1 = P \times h \times hr} \tag{1}$$

Where; HR is Biomass Resource Potential (tonnes/year), excluding inorganic materials.

P is Annual bio-waste production (tonnes/year), including inorganic materials.

h is harvest residue ratio (2.03)

hr is harvest residue recoverability ratio (0.50)

NOTE: Kaunda Square WWTP alone is capable of producing about 10 Tipper Trucks of eutroweed by 20 Tonnes twice per year. This brings us to P being equal to 400 Tonnes/year.

Therefore, $HR_1 = 400 \times 2.03 \times 0.50$

$HR_1 = 406$

$\boldsymbol{HR_1 = 406\ Tonnes\ of\ eutroweed/year}$

b. Biomass Feedstock from Sludge ($\boldsymbol{HR_2}$)

According to desktop data collected from Kaunda Square WWTP, the minimum and maximum influent flow rates for the year 2023 was 40litres/second and 150litres/second which gave rise to an average Q of 95litres/second. However, there are 31,557,600 seconds in one year. The amount of Influent into the sewer ponds was found as follows;

$Influent = average\ flow\ rate\ (Q) \times time\ (t)$ (2)

$$Influent = 95\frac{litres}{second} \times 31{,}557{,}600\frac{seconds}{1} = 2{,}997{,}972{,}000\ Litres$$

$Influent = 2{,}997{,}972{,}000\ Litres \approx 2{,}997{,}972m^3 of\ wastewater\ per\ year$.

The volume of sludge generated in a WWTP is only approximately 2% of the volume of influent wastewater that was treated. Therefore, HR_2 is only 2% of $2{,}997{,}972m^3$ by volume. $HR_2 = 2{,}997{,}972m^3 \times 0.02 = 59{,}959.44m^3$ by volume. However, the density of dry sludge is approximately 1.3kg/m^3. Therefore, m$ass\ of\ sludge = 1.3kg/m^3 \times 59{,}959.44m^3$

$Mass\ of\ sludge = 1.3kg/m^3 \times 59{,}959.44m^3$.

$\boldsymbol{HR_2 = 77{,}947.272Kg\frac{sludge}{year} \approx 77.947\ Tonnes\ of\ sludge/year.}$

c. Total Feedstock Available at WWTP ($\boldsymbol{HR_{Total}}$)

The total biomass Feedstock (HR_{Total}) available at the WWTP was found by adding the biomass feedstock for eutroweed (HR_1) and that for sludge(HR_2) as expressed in mathematical form below;

$\boldsymbol{HR_{Total} = HR_1 + HR_2}$ **(3)**

$where\ HR_1 = 406\ tonnes; and$

$HR_2 = 77.947\ tonnes$

Therefore, $HR_{Total} = 406\ tonnes + 77.947\ tonnes = 483.947 tonnes$

$\boldsymbol{HR_{Total} = 483.947\ Tonnes\ of\ Biomass\ Feedstock\ available\ at\ Kaunda\ Square\ WWTP\ per\ year.}$

2.3.2. Biogas Production Potential

In order to get uniform and true representative results, data capture was done every after five days at 05:00pm and recorded as shown in Table 1 right at the site of experiments. Note should be taken that on day negative 5 (five days before onset of experiment), the metallic drum-bio digester was injected with one hundred grams (100g) of dry cow dung.

This cow-dung was meant to stimulate the growth of methanic enzymes and microorganisms while the intended feedstock of 9.6 kilogram of bio-waste was fed into the digester on day number zero to indicate the onset of the experimentations. Nonetheless, it was also worth noting that there was an initial addition of one hundred grams (100g) of cow dung into the Bio digester prior to the addition of the feedstock of interest. Therefore, there was need to subtract the component of biogas that was generated from this amount of cow dung. [19] indicated that a 1Kg of cow dung produces an average of 22.5 litres of biogas. Based on this finding scholar, the amount of biogas generated from 100g of cow-dung stimulus was calculated as follows;

$$1000g\ cow\ dung\ \rightarrow 22.5l\ biogas$$

$$100g\ cow\ dung\ \rightarrow x\ l\ biogas\ \rightarrow x = 2.25l\ biogas \tag{4}$$

This entails that 2.25 litres of harvested biogas was a contribution from the 100 grams of cow-dung that was inoculated on day number negative zero just in order to stimulate methanic microorganisms. These 2.25 litres was subtracted from the total biogas of 17.2 litres in order to only remain with biogas that was produced from the digestion of bio-waste from the wastewater treatment plant. Eventually, the total amount of biogas produced from 9.6Kg of bio-waste reduces from 17.2 liters to 14.98 liters after taking away the 2.25 liters effect from the cow-dung. Table 1 shows biogas generated from specified amount of biomass feedstock.

***Table 1**. Biogas generated from specified amount of biomass feedstock*

		AMOUNT OF BIOGAS GENERATED AND CAPTURED (m^3)			
HRT in Days (d)	**Amount of feedstock (kg) (Batch Reactor)**	**Balloon Method (A)**	**Water Displacement Method (B)**	**Average $\frac{A+B}{2}$**	**Average as converted into Grams (g)**
0	9.6	0	0	0	0
5	9.6	0.0001	0.0002	0.00015	0.17
10	9.6	0.0152	0.0117	0.01345	15.0
15	9.6	0.0170	0.0150	0.01600	18.4
20	9.6	0.0178	0.0166	0.01720	19.78
25	9.6	0.0178	0.0170	0.0174	20.01
30	9.6	0.0179	0.0165	**0.0172**	19.78

If we get back to the earlier information provided by [3] about the percentage (%) composition of biogas that leaves the digester, it is possible to breakdown respective amounts of each constituent as follows;

a. Methane (CH_4) content in biogas is about 65%:

$$\therefore 14.98l\ \times 0.65 = 9.737 litre\ of\ pure\ \text{CH4 was harvested from 9.6Kg of biowaste} \tag{5}$$

b. Carbon dioxide (CO_2) occupies 30% of the biogas:

$$\therefore 14.98l\ \times 0.3 = 4.494\ litres\ of\ CO_2\ \text{was harvested from 9.6Kg of biowaste.} \tag{6}$$

c. Hydrogen sulphide (H_2S) is only 2% of the biogas:

$$\therefore 14.98l\ \times 0.02 = 0.3\ litres\ (300mls)\ of\ H_2S\ \text{was produced} \tag{7}$$

d. Trace amount of other gases such as mercaptans, oxygen (O_2) and nitrogen (N_2) takes up the remaining 3% of biogas:

$$\therefore 14.98l\ \times 0.03 = 0.45\ litres\ of\ \text{trace gases was produced} \tag{8}$$

The preceding data was found and computed based on a small prototype Metallic-drum Bio-digester that was used to anaerobically digestate 9.6 Kg of bio-waste feedstock at experimental stage. Therefore, the findings were scaled up to a level of a Wastewater Treatment using the conversion ratio of 1: 50,411 as computed from the ratio of biomass available as feedstock at Experimental level to Biomass Feedstock available at Kaunda Square WWTP level. Table 2.0 provides the scaled-up parameters from experimental level as conducted in a Drum-Bio digester to what would be expected if a Bio digester was designed and constructed to handle all the bio-waste streams at Kaunda Square Wastewater Treatment Plant.

Table 2. *Scaled-up parameters from experimental level to the expected if a Bio digester was designed and constructed at Kaunda Square Wastewater Treatment Plant.*

S/N	PARAMETERS	EXPERIMENTS AT DRUM BIODIGESTER LEVEL	KAUNDA SQUARE WASTEWATER TREATMENT PLANT LEVEL
1	Biomass available as feedstock	9.6 Kg	483,947 Kg
2	Biogas production potential	14.98 liters((17.23 g)	755,156.78 liters(868.43Kg)
3	Methane (CH4) production @ 65%	9.737 liters(11.20 g)	490,851.91 liters(564.48Kg)
4	Carbon-dioxide (CO2) @ 30%	4.494 liters(5.17g)	226,547.04 liters(260.53Kg)
5	Hydrogen Sulphide (H2S) @ 2%	0.3 liters (0.35g)	15,103.14 liters(17.37Kg)
6	Trace gases e.g. water vapour, methanethiol, ethanethiol, cysteine, coenzyme-A, oxygen (O2) and nitrogen (N2) @ 3%	0.45 litres(0.52g)	22,654.70 litres(26.05Kg)

2.3.3. Environmental Impact of Harvesting Biogas

The assessment of environmental impacts of harvesting biogas was found using the Global Warming Potentials (GWPs) for respective constituents of the yielded biogas. GWP were used to estimate, compare and aggregate the relative climate effects of the harvested greenhouse gases (GHGs) methane, carbon dioxide and water vapour that are present in biogas. GHGs are a measure of the relative radiative effect of a given substance compared to another, integrated over a chosen time horizon. A reference gas, carbon dioxide, is always assigned a GWP of one and other GHGs are thus expressed as Carbon dioxide equivalents ($CO_{2\,Equivalents}, also\ written\ as\ CO_{2\,Eq}$).

The emission values in mass units were multiplied by the GWP of the relevant gas in order to yield emissions in CO_2 equivalents. However, the GWP values for H_2O, CO_2 and CH4 were already given by [2] and [16] as 0.0005, 1 and 21 respectively over a time horizon of 100 years although that of H_2O is negligible but can still function as a greenhouse gas because it has a profound infrared absorption spectrum with more and broader absorption bands than CO_2. Table 3. below summarizes the GWP for GHGs of interest in this study.

Table 3. Greenhouse gases, their atmospheric lifetime and respective Global Warming Potentials

GREEN HOUSE GAS(CHG)	ATMOSPHERIC LIFE TIME (YEARS)	GLOBAL WARMING POTENTIAL(GWP)
Carbon dioxide (reference gas)	variable	1 (reference value)
Methane	12	21
Water vapour		0.0005
Nitrous Oxide	114	310

In order to convert emission values into CO_2 equivalents, the mass units (Kg in this study) wer multiplied by the GWP of the respective GHG and came up with the following findings;

a. Carbon dioxide (CO_2): the mass of carbon dioxide was found to be 260.53Kg and when converted into carbon dioxide equivalents it remains the same since it is a reference gas whose GWP is 1;

$$\therefore CO_2.CO_{2Eq} = GWP \times mass\ (Kg) \tag{9}$$

$$\therefore CO_2.CO_{2Eq} = 1 \times 260.53Kg \tag{10}$$

$$\therefore \boldsymbol{CO_2.CO_{2Eq} = 260.53KgCO_{2Eq}} \tag{11}$$

b. Methane (CH_4): the mass of methane was found to be 564.48Kg and was converted into carbon dioxide equivalents as follows;

$$\therefore CH_4.CO_{2Eq} = GWP \times mass\ (Kg) \tag{12}$$

$\therefore CH_4.CO_{2Eq} = 21 \times 564.48\text{Kg}$ (13)

$\boldsymbol{\therefore CH_4.CO_{2Eq} = 11,854.08KgCO_{2Eq}}$ (14)

c. Total amount of carbon dioxide equivalents ($CO_{2Eq.Total}$):

$\therefore CO_{2Eq.Total} = CO_2.CO_{2Eq} + CH_4.CO_{2Eq}$ (15)

$\therefore CO_{2Eq.Total} = 260.53KgCO_{2Eq} + 11{,}854.08KgCO_{2Eq}$ (16)

$\boldsymbol{\therefore CO_{2Eq.Total} = 12,114.61KgCO_{2Eq}.}$ (17)

2.3.4. Economic Benefits of Harvesting Biogas

The economic benefit of biogas lies in its potential to produce power and the usage of digestate as fertilizer for agricultural activities. Therefore, the bio-energy from the feedstock was calculated using the formular for Economic Power Potential (EPP) as indicated below.

$\text{EPP} = \frac{\text{BIOp}}{[\text{Load Factor } (0.91) \text{ x } 8760 \text{ x } 3.6 \text{ x } 1000]}$ (MW) (18)

But BIOp = HR x CV (19)

Where; BIOp is Bioenergy Resource Potential (MJ) and CV is Heating Value (MJ/kg) which is 19MJ/Kg for eutroweed (equivalent to maize stover) and the CV for Sludge is 18MJ/Kg (equivalent to maize cob, the staple food of Zambia). Therefore, bioenergy potential for Eutroweed (BIO_{p1}) whose heating value (CV) is 19Kg/MJ was calculated as follows;

a. Bioenergy Resource Potential for Eutroweed ($\boldsymbol{BIO_{p1}}$)

$HR = HR_{Total} = 483.947Tonnes$

$CV = 19MJ/Kg$

$BIO_{p1} = HR \times CV$

$BIO_{p1} = 483.947 \times 19$

$\boldsymbol{BIO_{p1} = 9,194.993MJ}$

b. Bioenergy Resource Potential for the Sludge ($\boldsymbol{BIO_{p2}}$)

$HR = HR_{Total} = 483.947\ Tonnes$

$CV = 18MJ/Kg$

$BIO_{p2} = HR \times CV$

$BIO_{p2} = 483.947 \times 18$

$$\boldsymbol{BIO_{p2} = 8,711.046MJ}$$

c. **Total Bioenergy Resource Potential (BIO_p)**

$$BIO_p = BIO_{p1} + BIO_{p2}$$

$$BIO_p = 9{,}194.993MJ + 8{,}711.046MJ$$

$$\boldsymbol{BIO_p = 17,906.039MJ}$$

Therefore, the Economic Power Potential (EPP) = $\frac{\text{BIOp}}{[\text{Load Factor } (0.91) \text{ x } 8760 \text{ x } 3.6 \text{ x } 1000]}$ (MW)

EPP = $\frac{17{,}906.039MJ}{[(0.91) \text{ x } 8760 \text{ x } 3.6 \text{ x } 1000]}$ (MW)

EPP = $\frac{17{,}906.039MJ}{28{,}697{,}760}$ (MW) =$6.24 \times 10^{-4}MW \approx 0.000624MW.$

Further, the digestate is another component of total amount of digestate that remains in a digester after all the four biochemical processes are completed was quantified by the help of the Law of Conservation of Mass which states that mass can neither be destroyed nor created at any point in time in any closed system [20]. This means that the mass of influent feedstock that was supplied to the biodigester equals the sum of mass of effluent of biogas produced by the anaerobic digestion and the retained digestate in the digester tank. Therefore, the total amount of Digestate (D) generated from the anaerobic digestion of bio-waste from a Wastewater Treatment Plant was found to be the difference between the amount of feedstock influent (I) and the biogas produced (B) plus the 2% of hydrogen sulphide (H_2S) added back to the digestate as expressed in mathematical way as follows.

$$D = (I - B) + H_2S \tag{20}$$

Where; $D = digestate\ (Kg)$

$I = Biomass\ or\ feedstock\ inffluent\ into\ the\ biodigester\ (Kg)$

$B = Biogas\ produced\ (Kg)$

$H_2S = 2\%\ of\ hydrogen\ feedstock\ added\ back\ to\ the\ digestate\ (Kg)$

Therefore, the total digestate (D) produced from the bio-chemical processes using the real scenario comes to;

$$D = (I - B) + H_2S$$

$$D = (483{,}947Kg - 868.43Kg) + 17.37Kg$$

$$D = (483{,}078.57Kg) + 17.37Kg$$

$$\boldsymbol{D = 483,095.94Kg\ of\ Digestate\ to\ be\ used\ as\ Fertiliser\ in\ Agriculture}$$

3. RESULTS AND DISCUSSION

This section of study endeavored to transform the raw data into useful information through graphical presentation of results and provision of discussions relevant to the research questions and in line with the topic of study. The total average amount of biogas that was produced from a 9.6kg of dry bio-waste from a wwtp was 14.98g which when scaled up to Kaunda Square WWTP level it comes to 868.43kg biogas production per year from the total biomass potential of 483,947Kg.

3.1. Results

This part of study included graphical presentation of data recorded about biogas production against hydraulic retention time (HRT) for the conducted Experiments A and B as well as for the control Experiment C as shown in Tables 4, 5 and 6 and Figures 7, 8, and 9 respectively below.

3.1.1. Biogas Production from Experiment A

Table 4. Data for biogas production for experiment A

Biogas (g)	x	0	0.12	17.48	19.55	20.47	20.47	20.59
HRT (days)	y	0	5	10	15	20	25	30

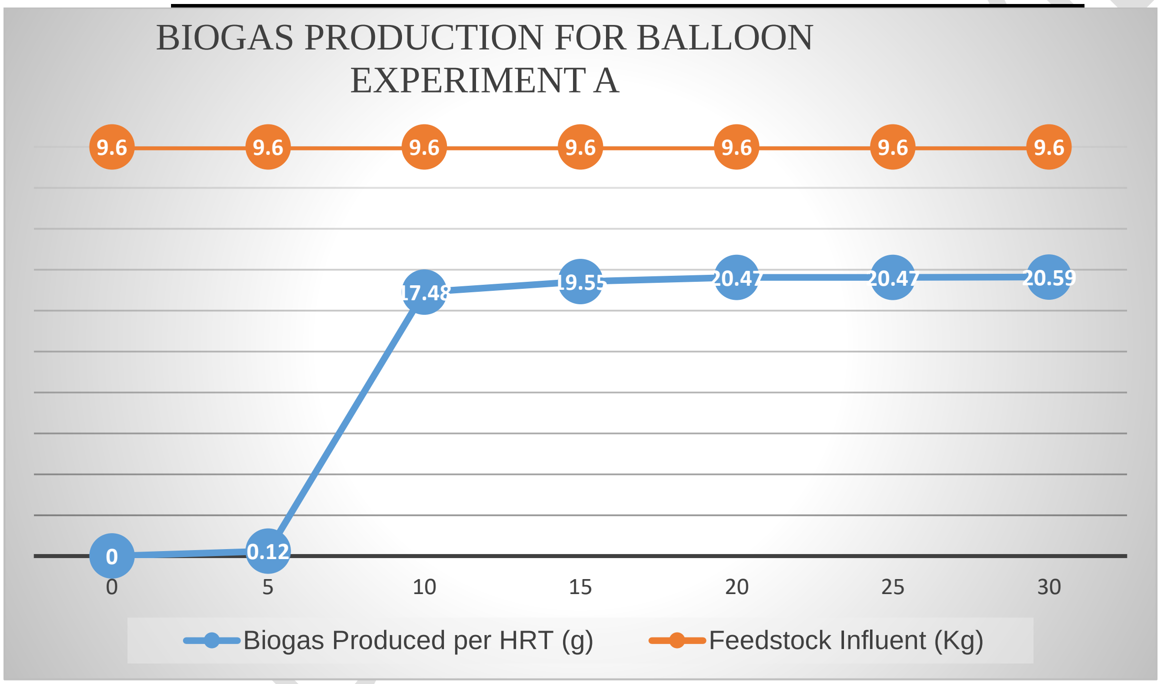

Figure 7. Graph showing the production of biogas for a balloon experiment A

3.1.2. Biogas Production from Experiment B

Table 5. Data for biogas production for experiment B

Biogas (g)	x	0	0.23	13.46	17.25	19.09	19.55	18.98
HRT (days)	y	0	5	10	15	20	25	30

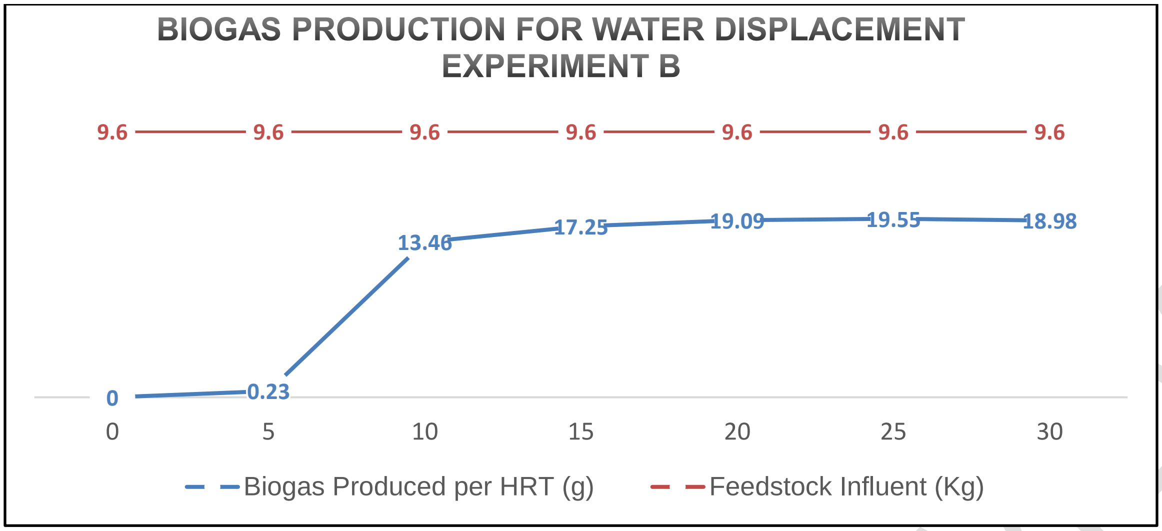

Figure 8. Graph showing biogas production for a water displacement experiment B

3.1.3. Mean Biogas Production for Experiments A and B

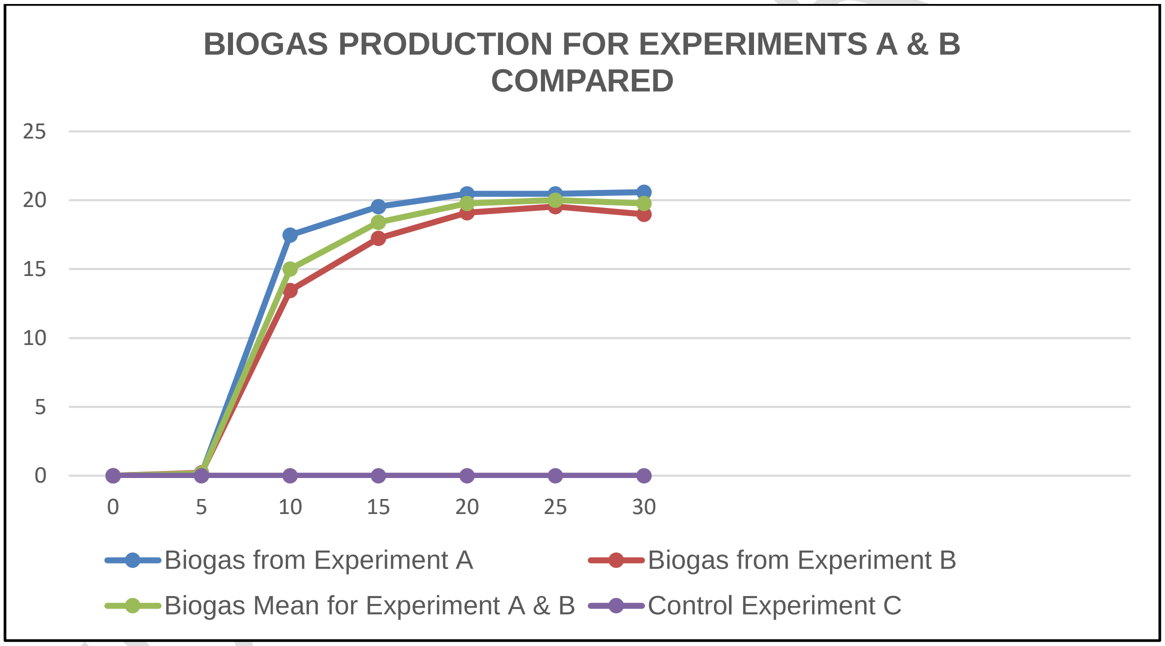

Figure 9. Graphs showing the mean (average) biogas production for experiments A and B (Data from Table 6)

3.2. Discussions

The study revealed that the total biomass potential available as feedstock at Kaunda Square Wastewater Treatment Plant was 483,947kg (483.947 tonnes) per annum. Since a 9.6kg of biomass feedstock used for Experiments **A** and B produced 0.0179M^3 and 0.0165M^3 of biogas in 30 days, the average monthly biogas production came to 0.0172M^3. However, the scaling-up of these experimental findings from 9.6kg experimental bio-waste feedstock to 483,947kg WWTP bio-waste feedstock yields a potential biogas production of 755,156.78 liters (868.43kg) per annum.

The total amount of greenhouse gases (GHGs) of environmental importance came from the summation of contributions of methane and carbon dioxide itself and was expressed as carbon dioxide equivalents (CO_{2Eq}**)**. The total value of the two

GHGs was found to be $12{,}114.61 KgCO_{2Eq}$ that had direct effect on global warming (GW) and climate change (CC). Therefore, the harvesting of biogas from a wastewater treatment plant means preventing from being emitted into the environmental of $12{,}114.61\mathrm{Kg}\boldsymbol{CO_{2Eq}}$ of GHGs that could otherwise have contributed towards the already felt effects of GW and CC. The digestate had its economic value in agricultural use where the potential stood at production of 9,662 by 50kg bags of nitrogen/sulphur rich organic fertilizer per annum. This organic fertilizer cannot only improve crop yields but also enhance soil fertility. The Economic Power Potential (EPP) of the harvested biogas was found to be $6.24 \times 10^{-4} MW (0.000624 MW)$, which electricity can be used to bridge the energy deficit in the nation amidst the drought Zambia has experienced in the recent past.

4. CONCLUSION

The harvesting of bioenergy through harvesting of greenhouse gases from bio-waste not only at a wastewater treatment plant but also at any other point of bio-waste generation can lead to dramatic contribution towards reduction of emission into the atmosphere of greenhouse gases. The biogas is a bioenergy that is green and clean source of energy that can be used for direct heating, lighting, drive engines and run turbines for electricity generation. Actually, this experimental study revealed that the biogas production potential is 868.43kg from the total biomass potential of 483.947 tonnes per annum at WWTP level.

The harvesting of biogas may therefore lead to climate control, reduced energy deficit, improve food security through increased crop production and enhances soil fertility. In addition to this, increased employment opportunities is another positive benefit of this project. Furthermore, the Carbon footprint of 12.115 tonsCO_{2Eq} that Kaunda Square Wastewater Treatment Plant alone would harvest per annum can be traded as Emission Avoidance Carbon Credits on Carbon Credit Marketplaces leading to a nation gaining some forex while mitigating the already felt effects of Global Warming and Climate Change.

CONFLICT OF INTEREST

We wish to confirm that there are no known conflicts of interest associated with this manuscript. We further confirm that there has been no financial support for this work that could have influenced its outcome and that the manuscript has been read and approved by all named authors to submit it for publication at the **Journal for Energy Research and Reviews** and that there are no other persons who satisfied the criteria for authorship but are not listed.

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