A COMBINED BIOGAS PLANT AND INCINERATOR SYSTEM FOR MUNICIPAL SOLID WASTE MANAGEMENT

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NIGERIA

OCTOBER, 2017

DECLARATION

I declare that the work in this dissertation entitled "A Combined Biogas Plant and Incinerator System for Municipal Solid Waste Management" has been carried out by me in the Department of Water Resources and Environmental Engineering, Ahmadu Bello University, Zaria. The information derived from literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation as far as I know was previously presented for another degree or diploma at this or any other Institution.

Abdul-Hakeem Ayodele BUSARI	……..	…….
Name of Student	Signature	Date

CERTIFICATION

This dissertation entitled "A COMBINED BIOGAS PLANT AND INCINERATOR SYSTEM FOR MUNICIPAL SOLID WASTE MANAGEMENT" by Abdul-Hakeem Ayodele BUSARI meets the regulations governing the award of the degree of Master of Science in Water Resources and Environmental Engineering of Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

Bismillahi al-Rahmani al-Raheemi. In the name of Allah, the generally merciful, the specially merciful. He was the One that placed so much importance on knowledge that His first revelation to the prophet of Islam was “Iqraa! Bismi robika” (Read, recite or rehearse in the name of your Lord). [Al-Qur’an 96:1] Alazii alama bil Qalami {He Who taught (the use of) the Pen} [Al-Qur’an 96:4], while His second revelation was “ Nun. Wa al-Qalami wa maa yasturuuna” {Nun. By the Pen and by the (Record) which (men) write,} [Al-Qur’an 68:1]

The prophet of Islam said “Seek knowledge, even in China” [Hadith Hasan Mashhur]

I therefore dedicate this endeavour to Allah, the Almighty, the Sublime, the Wise and all the practitioners in the temple for the search for knowledge. May He consider it a service to His creations and reward me abundantly on the day of recompense. Amin.

ABSTRACT

This study, assessed the potentials of generating biogas from the organic fraction of municipal solid wastes to fuel an incinerator which is then used to burn the residual combustible solid waste. Municipal solid waste from Ahmadu Bello University (ABU) commercial market was collected, grinded and mixed with intestinal waste from slaughtered cattle at Zango abattoir, Zaria in a 2:1 ratio by volume. The mixture was diluted with water in a 1:1 ratio by volume to form a slurry and digested anaerobically in a digester

The efficacy of the digester in producing biogas were in three (3) phases. Lowest between day 3 – 11; 0.143m^3 (0.018m^3/kg), highest between day 15 – 55; 1.353m^3 (0.034m^3/kg) and medium between day 55 – 94; 1.208m^3 (0.031m^3/kg)

Fertilizer values based on the ratios of N: P: K: Mg were 28: 1: 22: 4; 1: 971: 821: 1995 and 10: 1: 59: 104 for digestate, bottom ash and combined digestate and bottom ash respectively.

Total Organic Carbon contents of the digested solid waste were0.1389 %, 0.8099 %, and 0.3008 % of the initial mass for digestate, Bottom ash and combined digestate and bottom ash respectively.

A small scale incinerator was built with the capacity to burn 1.8m^3 of solid waste per day burn cycle. A biogas air mixer was developed to ensure good combustion by the biogas burner. The biogas burnt with a blue flame measured at 870^{0}C and a calorific value of 16,000J/g while the incinerator was able to achieve an average operating temperature of 930^{0}C with a percentage waste reduction of 80 % per hour with 4.5 % as bottom ash. Biogas consumption by the incinerator's auxiliary burner was 0.0071m^3/min with adequate flame stability during the process. Ratio of gas used to the solid waste combustion was 1: 78: 1 v/v per hour.

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ABBREVIATIONS, DEFINITIONS, GLOSSARY AND SYMBOLS

ABU	Ahmadu Bello University
AD	Anaerobic Digestion
ARIA	Analysis, Research and Information on Accidents
ASBR	Anaerobic Sequencing Batch Reactors
BARPI	Bureau for Analysis of Industrial Risks and Pollution
BOD	Biological oxygen demand; measures the dissolved oxygen consumed by organisms to oxidize organic compounds
CCME	Canadian Council of Ministers for the Environment
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
COD	Chemical oxygen demand; this is a measure of all organic compounds that can be chemically oxidized
CSTR	Continuously Stirred Tank Reactors
Defra	Department for Environment, Food and Rural Affairs
EfW	Energy-from-Waste
EIA	Environmental Impact Assessment
EU	European Union
FB	Fluidised Bed
FEPA	Federal Environmental Protection Agency
FFR	Fixed Film Reactor
FMOE	Federal Ministry of Environment
FRNOG	Federal Republic of Nigeria Official Gazette
FVW	Fruits and Vegetable Wastes

GP®	Plastic water tank produced by GeePee Industries Limited
H_2S	Hydrogen Sulphide
HRT	Hydraulic retention time
IAR	Institute for Agricultural Research
IED	Industrial Emission Directive
iFi	Individual Intake Fraction
Maishara	Name for domestic waste disposal practitioners in Hausa language
MSW	Municipal Solid Wastes
NAPRI	National Agricultural Products Research Institute
NESREA	National Environmental Standards Regulatory and Enforcement Agency
OFMSW	Organic Fraction of Municipal Solid Wastes
OLR	Organic Loading Rate
PPR	Polypropylene
PSP	Private Sector Participants
RDF	Refuse Derived Fuel
RT	Residence Time
SBH	Solid Bed Hydrolyser
SRT	Solids Retention Time
Tigre®	Plastic pipes and fittings manufactured by Tigre Industries Limited
TOC	Total Organic Carbon
TS	Total Solids
TVS	Total Volatile Solids
UASB	Upflow Anaerobic Sludge Blanket
UASB	Upflow Anaerobic Sludge Blanket

UK	United Kingdom
USA	United States of America
VFA	Volatile Fatty Acids
WHO	World Health Organisation
WID	Waste Incineration Directive
WREE	Water Resources and Environmental Engineering
WtE	Waste-to-Energy

CHAPTER ONE

INTRODUCTION

1.1 General Background of the Study

Communities around the world generate refuse of diverse nature and complexities, the disposal of which poses serious challenges to waste management systems. Environmentally, sustainable waste management requires the reduction of their pollution potential as well as minimisation of their volume for easier handling and disposal. Above all, the conversion of such waste through transformation and re-use has led credence to the current “energy from wastes” and “wastes to wealth” concepts.

Solid wastes accumulate in the environment in increasing magnitude and sophistication, be it in urban, semi-urban and rural communities. Their sources are as diverse as man’s activities, ranging from households to commercial ones such as markets, hotels and restaurants or processing units like abattoirs. These subsequently constitute complex municipal solid wastes in cities and municipalities (Mohammad *et al.*, 2012)

Urban and semi-urban communities waste management practises that evolved include the periodic collection by Private Sector Participants (PSP) and organisations licensed by the local government or waste management authorities at regulated service rates for further disposal at what can be termed formal dump sites. Sometimes, periodic collection are by sole entrepreneurs (usually called "*Maishara*") at negotiated service rates for further disposal at the formal, and most times informal, dump sites. A lot of the time the practise is just by indiscriminate dumping; a practice where people just dump their solid wastes anywhere they could. The formal dump sites are those operated by agencies of government with the responsibility for waste management. The informal ones are usually communal designated dump sites while according to Mohammad *et al.*, (2012)

indiscriminate dumping is carried out at most times in undeveloped and semi-developed plots of land within communities. At times they are natural depressions and gorges; usually the result of gully erosion, and sometimes waterways, drainage channels and expressway road sides.

For specialized environment like abattoirs, vegetable/fruits markets, restaurants and hotels, the solid wastes are usually collected by the PSP operators, the local government or waste management authority at particular service rates while the semi-solid waste, liquid waste and waste water usually at-times involve the construction of expensive sewerage and waste water treatment systems, which most times fail within a very short time due to operation and maintenance challenges and most of the time, the semi-solid, liquid and waste water are just washed down or allowed to flow into drains and natural waterways causing serious environmental nuisance.

The organic portion of waste collected decomposes in the presence or absence of air. In the presence of air the end result is unpleasant odours, fly nuisance, unsightly environment and leachates. In the absence of air, the end result is **biogas;** Hydrogen Sulphide (H_2S), Carbon Dioxide (CO_2), Methane (CH_4), and some trace gases. This biological decomposition of organic matter in the absence of oxygen is referred to as anaerobic digestion (AD). Biogas can be produced from the organic wastes by means of an AD system. The biogas so generated can then be used to operate an incinerator designed and built for the residual combustible wastes generated in the community. Biogas thus described is a renewable fuel produced from controlled waste degradation through anaerobic digestion which is basically a simple process carried out in a number of steps that can use almost any organic material as substrate. It is the process that occurs in digestive systems, in marshes, in rubbish dumps, septic tanks and the Arctic Tundra

(Igboro, 2011). The process does not require large expenditures of energy, as it is biologically driven by a mixed culture of bacteria in the absence of oxygen.

Graunke and Wilkie, (2008), with an illustrated biogas cycle (Figure 1.1) shows why biogas is considered to be carbon neutral because all of the carbon released during its combustion has been recently taken from the atmosphere through photosynthesis when compared with fossil fuels that have stored carbon for millions of years. Biogas is therefore, a sustainable alternative to natural gas. Since anaerobic digestion only releases carbon to the gas phase, the other nutrients (Nitrogen, Phosphorus and Micronutrients) remain in the effluent, which makes it a highly organic fertilizer and soil conditioner.

The slurry which is the by-product of the digester and the ash which is the by-product of the incinerator can be mixed and tested for possible use as a soil conditioner.

Furthermore, energy recovery in the form of heat; generated in the course of burning waste in the incinerator, is possible to which a variety of uses can be found. Examples of such uses are hot water for washing plates and utensils in restaurants, for bathing and laundry in homes and hotels, for meat processing at abattoirs, or for heating in a drier.

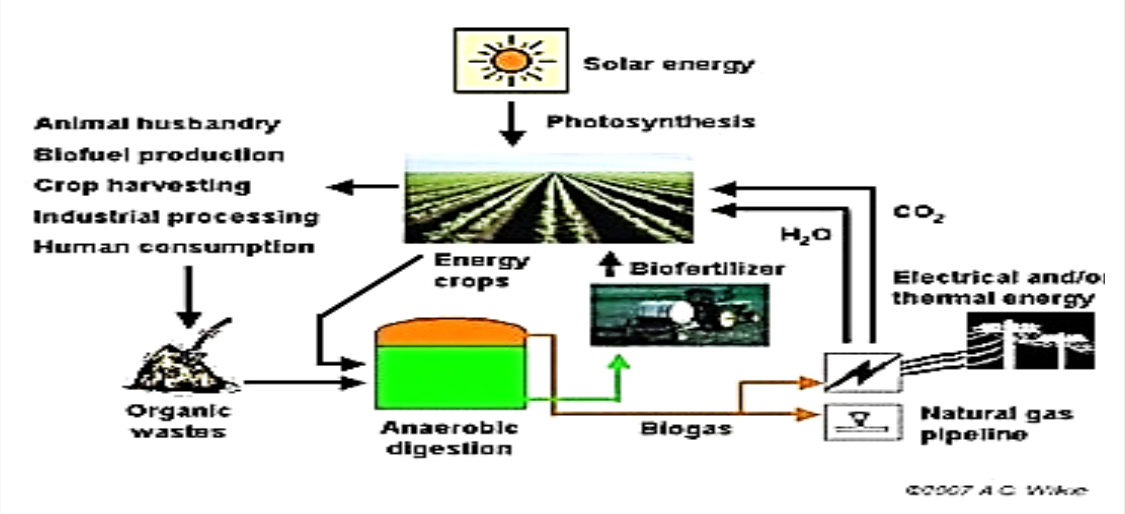


Figure 1.1: Biogas Cycle (Graunke and Wilkie 2008)

1.2 Statement of Research Problem

The rural-urban shift has led to a rapid growth in the populations of many urban and semi-urban communities with the concomitant increase in the quantity of municipal solid wastes (MSW) generated. As a result solid wastes have become a serious nuisance and environmental challenge in many Nigerian cities (Plate I). On the other hand, places like restaurants, hotels, abattoirs and vegetables/fruit markets generate organic wastes at various stages of decomposition which causes a degraded and extensively fouled environment when they could be used as perfect feedstock for a biogas plant.

The current mode of managing these municipal solids wastes has fallen far short of the necessary requirements for a healthy, safe and aesthetic environment proliferating obnoxious odours and a preponderance of disease vectors. Leachates from these dump sites contaminate ground water resources and during rainfall generate run-offs which contaminate surface water resources. This therefore underscores the need for methods of disposal which are economic and environment friendly. Such methods require a waste to wealth transformation through an environmentally sustainable reuse programme to transform the waste to bioenergy resource for household and commercial uses including management of the solid wastes as proposed in this study



Plate I: Municipal Solid Wastes Transfer Station on Abuja – Keffi expressway, Mararaba, Nassarawa State

1.3 Justification of the Study

In an effort to create an environment that is safe, healthy and aesthetically pleasing, a combined biogas plant and incinerator system is an attractive option for the management of municipal solids wastes. The organic fraction of the municipal solid waste that produces the obnoxious odours during decay can be utilized in the digester as feedstock thereby reducing or even eliminating their menace and nuisance in many cities in Nigeria (Akinbami *et al.,* 2001). The Biogas generated can be used in the incinerator helping to reduce the amount of greenhouse gas like methane that would have otherwise been released into the atmosphere (Xuereb, 1997)

The combustibles making up the residual municipal solid waste is burnt in the incinerator reducing them to bottom ash while the energy recovery that is possible in the form of heat from the incinerator could be put to a variety of uses depending on the environment in which the system is in operation. Examples of such uses are hot water for plates and utensils washing in a restaurant, bathing and laundry in a hotel and meat processing at an abattoir, or for drying when used in conjunction with an air blower in a drier resulting in huge savings in heating costs.

When used in specialized environments like an abattoir/market or big hotels /restaurants; the utilization of the organic wastes would reduce the loading of any waste water/sewage treatment plant in place with a huge cost saving in its sizing and operation.

Although, on burning biogas, carbon dioxide is released it is not considered that this is a significant contribution to the net global carbon dioxide level because it originated from plants, which have absorbed it from the atmosphere in the first place. Hence, this carbon dioxide does not make a net contribution to the greenhouse effect (Xuereb, 1997; Graunke and Wilkie, 2008)

Finally, the use to which the by-products; digestate from the digester, bottom ash and energy recovery from heat generated in the incinerator, can be put to, makes this combined system to perfectly align with current waste management strategies and practices.

1.4 Aim and Objectives

This study aims at the management of municipal solids wastes using a combined biogas plant and incinerator system. The specific objectives are:

1. to design and construct a biogas plant as well as an incinerator
2. to use the gas generated by the biogas plant as primary fuel to operate the incinerator to burn the residual combustible solid waste and analyse the performance of the two treatment systems
3. to carry out laboratory analysis of the by-products of the two treatment systems, separately, and mixed, with a view to making necessary recommendations for use.

1.5 Scope and Limitations of the Study

This study is limited to the use of municipal solid wastes in the waste dump at the ABU community market behind the Faculty of Education (Plate II)



Plate II: Municipal solids waste at the community market behind ABU, Zaria Faculty of Education

and at the waste dump in the Water Resources and Environmental Engineering (WREE) department (dept.), Ahmadu Bello University (ABU), Zaria (Plate III) mixed with cattle dung and ruminant intestinal waste from Zango abattoir, Zaria shall be utilized to enrich the biogas plant substrate to hasten the anaerobic digestion process and thus bridge the gas production lag phase.

But these wastes could hardly be introduced into the digester as produced, so the combined system has to be complimented with a crushing unit to pulverise the waste to increase its surface area for bacterial action and digestion.

The residual combustible waste introduced into the incinerator is limited to the post-sorted municipal solid wastes (plastics especially, removed) in the WREE dept. waste dump. The scope of the study did not include analysis or scrubbing of the flue gases from the incinerator nor that of the biogas from the digester as long as it is functional for use in the incinerator as is.



Plate III: Municipal solid waste in the WREE dept., ABU, Zaria waste dump

CHAPTER TWO

LITERATURE REVIEW

2.1 Municipal Solid Wastes

Generally, MSW or refuse is regarded as useless material that is unwanted and therefore discarded. Bryne (1997) was more comprehensive in his description of waste "as material which has no direct value to the producer and so must be disposed of". This could be why Bailie *et al.*, (1999) insist that "for practical purposes, the term waste includes any material that enters the waste management system".

2.1.1 Characteristics and Properties

Ogunbiyi (2001), classified wastes as gaseous, liquid or solid depending on their phase. He went on to note that it is possible to have solid wastes intermixed with liquid wastes but its non-flowing nature requires its continual retention at the site of generation or deposition until it is removed for disposal. Kiely, (1998) and Bailie *et al.*, (1999) were in agreement that MSW in particular, comprises small and moderately sized solid-waste items from houses, businesses and institutions, while Bryne, (1997) classified municipal waste, as that, generated from urban areas, particularly houses and shops.

2.1.2 Treatment / Management

One of the guiding principles of current waste treatment/management practices is the concept of a hierarchy of waste management options, where the most desirable option is not to produce the waste in the first place (Waste Prevention) and the least desirable option is to dispose of the waste with no recovery of either materials and/or energy. Between these two extremes there are a wide variety of waste treatment options that may be used as part of a waste management strategy to recover materials or generate energy from the wastes.

Anaerobic digestion (to produce usable biogas) and incineration (to generate energy), the twin arms of this study falls into this latter category of current waste management strategies

2.2 Anaerobic Digestion

Punmia *et al.,* (2005) submitted that AD consists of two distinct stages in four processes which occur simultaneously, in the digestion of organic matter. The first stage known as acid fermentation consists of hydrolysis, acidogenesis and acetogenesis. Hydrolysis is the process where complex organic materials are broken down into their constituent parts; soluble monomers. This is followed by acidogenesis in which liquefaction of high molecular weight organic compounds and conversion to organic acids by acid forming bacteria occurs and finally by acetogenesis, where acetate is formed. Acetic acid, propionic acid and butyric acid are the most common end products of this first stage. The second stage known as methane fermentation or methanogenesis is gasification of the organic acids to methane and carbon dioxide by acid splitting methane forming bacteria. Metcalf and Eddy (2003) on the other hand described as three, the basic steps in the overall anaerobic oxidation of a waste viz hydrolysis, fermentation and methanogenesis in agreement with McCarty and Smith, (1991) as illustrated in Figure 2.1

2.2.1 Biochemical Reactions

Themelis and Verma, (2004) posited that an approximate chemical formula for the mixture of organic waste is $C_6H_{10}O_4$. A hydrolysis reaction where the organic waste is broken down into simple sugar (glucose) is as shown in Equation 2.1

$$C_6H_{10}O_4+2H_2O \rightarrow C_6H_{12}O_6+2H_2 \qquad \text{Equation 2.1}$$

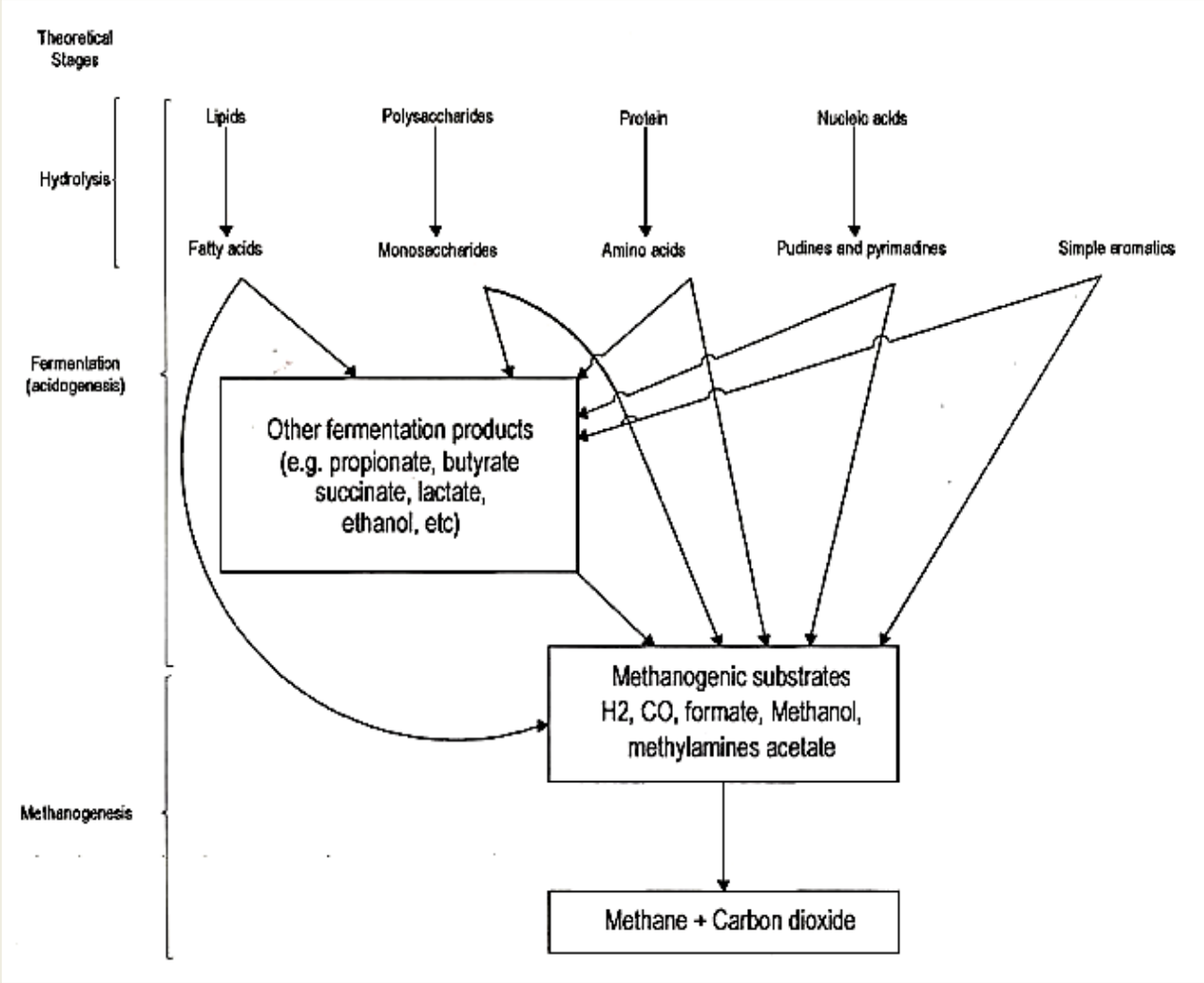


Figure 2.1: Anaerobic Process Schematic of hydrolysis, fermentation and methanogenesis (McCarty and Smith, 1991)

Ostream, (2004) went on to show how the product of hydrolysis are converted into simple organic compounds mostly short chain (volatile) acids (propionic, formic and lactic acids), ketones (e.g. ethanol, methanol, glycerol and alcohols) with typical reactions in this stage as shown in Equations 2.2 and 2.3.

$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$ Equation 2.2

$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$ Equation 2.3

Thermelis and Verma, 2004 stated further that acetogenesis is often considered with acidogenesis to be a part of a simple acid forming stage. It is however important to distinguish the two stages because Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) are reduced through these pathways. Acetogenesis occurs through carbohydrate fermentation in which acetate is the main product including other metabolic processes. The result is a combination of acetate, CO_2 and H_2.

The role of hydrogen is of critical importance in this reaction. The formation of hydrogen gas as shown in Equation 2.1 inhibits the oxidation process under standard conditions with the reaction only proceeding when the partial pressure of H_2 is low enough to thermodynamically favour the conversion. The presence of hydrogen scavenging bacteria that consume hydrogen thus lowering the partial pressure is necessary to ensure thermodynamic feasibility of the reactions and thus the conversion to biogas of all the acids. Mata-Alvarez *et al.*, (2003) noted that the concentration of hydrogen measured by this partial pressure is therefore an indication of the health of an anaerobic digester with typical reactions at this stage as shown in Equation 2.4 (Conversion of glucose to acetate) and 2.5 (Conversion of ethanol to acetate)

$$C_6H_{12}O_6 + 2H_20 \rightarrow 2CH_3\,COOH + CO_2 + 4H_2 \quad \text{Equation 2.4}$$

$$2CH_3OH + 2H_2O \rightarrow 2CH_3\,COOH + 4H_2 \quad \text{Equation 2.5}$$

According to Gas Technology Inc. (2003) (cited in Hayes, 2004), the transition of the substrate from organic material to organic acids causes the pH of the system to drop. This is beneficial for the acidogenic and acetogenic bacteria but problematic for the methanogenic bacteria of the final stage of these biochemical reactions.

Methanogenesis is the rate-controlling activity of this anaerobic digestion process since methanogens have a much slower growth rate than acidogens (Ostream, 2004). The bacteria involved in this stage are the type found in the guts of herbivores. They convert the soluble matter into methane. They are very sensitive to pH changes preferring a neutral or slightly alkaline environment. If the systems pH is allowed to fall below 6 these group of bacteria cannot survive. Some of the reactions mostly are as follows:

Ethanol converted to acetate and methane

$2CH_3\ CH_2OH + CO_2 \rightarrow 2CH_3COOH + CH_4$ Equation 2.6

Acetate further degraded to methane and CO_2

$CH_3COOH \rightarrow CH_4 + CO_2$ Equation 2.7

Alcohol converted to methane

$CH_3OH + H_2 \rightarrow CH_4 + H_2O$ Equation 2.8

Carbon dioxide reduction by hydrogen to methane

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ Equation 2.9

(Ostream, 2004; Igboro, 2011)

Finally, Madigan *et al.*, (1997) listed the methanogenic reactions involving the oxidation of hydrogen formic acid, carbon monoxide, methanol, methyl amine and acetate respectively as follows:

$4H_4 + CO_2 \rightarrow CH_4 + 2H_2O$ Equation 2.10

$4HCOO^- + 4H^+ \rightarrow CH_4 + 3CO_2 + 2H_2O$ Equation 2.11

$4CO + 2H_2O \rightarrow CH_4 + 3CO_2$ Equation 2.12

$4CH_3OH \rightarrow 3CH_4 + CO_2 + 2H_2O$ Equation 2.13

$4(CH_3)_3\ N + H_2O \rightarrow 9CH_4 + 3CO_2\ 6H_2O + 4NH_3$ Equation 2.14

$CH_3COOH \rightarrow CH_4 + CO_2$ Equation 2.15

In the reaction for the aceticlastic methanogens as given by Equation 2.15 the acetate is cleaved to form methane and carbon dioxide.

2.2.2 Stoichiometry

A Chemical Oxygen Demand (COD) balance can be used to account for the changes in COD during fermentation. Instead of oxygen accounting for the change in COD, the COD loss in the anaerobic reaction is accounted for by the methane production. By stoichiometry the COD equivalent of methane can be determined. The COD of methane is the amount of oxygen needed to oxidize methane to carbon dioxide and water.

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ Equation 2.16

From the above, the COD per mole of methane is 2 (32g O_2/mole) = 64g O_2/mole CH_4. The volume of methane per mole at standard conditions (0^0C and 1 atm) is 22.414 litres. So the CH_4 equivalent of COD converted under anaerobic condition is 22.414/64 = 0.35 litres CH_4/g COD at standard condition. (Metcalf and Eddy 2003).

The quantity of methane at other than standard conditions is determined by using the universal gas law (Equation 2.17) to determine the volume of gas occupied by one mole of CH_4 at the temperature in question. (Metcalf and Eddy, 2003)

$$V = \frac{nRT}{P}$$ Equation 2.17

Where *V*= Volume occupied by the gas, *l*

n= Moles of gas, mol

R= Universal gas low constant 0.082057 atm.*l*/mol.k

T= Temperature, K (273.15 + ^{0}C)

P= Absolute pressure, atm

Thus at 35^0C the volume occupied by one mol of CH_4 is given by

$$V = \frac{(1mol)\left(0.082057\ atm.\frac{l}{mole}.k\right)[(273.15+35)K]}{1.0atm} = 25.29\ l$$

Because the COD of one mol of CH_4 = 64g, the amount of CH_4 produced per unit of COD converted at 35^0C under anaerobic condition is therefore

(25.29*l*)/(64g COD/mol CH_4) = 0.40 *l* CH_4/g COD

2.2.3 Microbiology and syntrophic relationships in fermentation

According to Metcalf and Eddy, (2003), the group of non-methanogenic microorganisms responsible for hydrolysis and fermentation consist of facultative and obligate anaerobic bacteria. Organisms that have been isolated from anaerobic digesters include *Clostridium spp, Peptococcus*, anaerobes, *Bifidobacterum spp, Desulphorvibrio spp, Corynebacterium spp*, *Lactobacillus, Actinomyces*, *Staphylococcus,* and *Escherichia coli*. Other physiological groups present include those producing Proteolytic, Lipolytic, Ureolytic or Cellulytic enzymes. The Micro-organisms responsible for methane production, classified as *archaea*, are strict obligate anaerobes. Many of the methanogenic organisms identified in anaerobic digesters are similar to those found in the stomach of ruminant animals and organic sediments taken from Lakes and Rivers. The principal genera of microorganisms that have been identified at mesophilic condition include the rods (*methanobacterium, methanobacillus*) and spheres (*methanococcus, methanothox* and *methanosarcina*). *Methanosarcina* and *methanothrix* (also termed *methanosaeta)* are the only organisms able to use acetate to produce methane and carbon dioxide. The other organisms oxidize hydrogen with carbon dioxide as the electron acceptor to produce methane.

Metcalf and Eddy, (2003) reported further that a syntrophic (mutually beneficial) relationship exist between the methanogens and the acidogens in which the methanogens convert fermentation end products such as hydrogen formate and acetate to methane and carbon dioxide. Normally, the hydrogen produced by the acidogens will inhibit the reaction process from moving forward but because the methanogens are able to maintain an extremely low partial pressure of the hydrogen through consumption and conversion, the equilibrium of the fermentation reaction is shifted towards the formation of more oxidized end products (e.g. formate and acetate). In effect the methanogenic organisms serve as a hydrogen sink that allows the fermentation reaction to proceed. If process upset occurs and the hydrogen produced is not utilized fast enough, the fermentation will be slowed with the accumulation of volatile fatty acids resulting in pH reduction which is unhealthy for the digester.

Finally, there are two rate-limiting concepts that are very important in anaerobic processes; the hydrolysis conversion rate and the soluble substrate utilization rate for fermentation and methanogenesis. The anaerobic process is more stable when the volatile fatty acids (VFA) concentration approach minimal level which can be taken as an indication that a sufficient methanogenic population exists and sufficient time is available for them to minimize hydrogen and VFA concentrations. This assertion was supported by Lawrence and McCarty, (1990) in their submission that the rate-limiting step is the conversion of the VFA's by the methanogenic organisms and not the fermentation of soluble substrates by the acidogenic bacteria. They therefore concluded that the methanogenic growth kinetics is of most interest in anaerobic process designs and appropriate solids retention times (SRT) as well as adequate factor of safety are selected based on kinetics and treatment goals.

2.3 End Products of Anaerobic Digestion

The end products of AD are biogas, liquid digestate and digester sludge (solid digestate). The components of the biogas are predominantly methane and carbon dioxide (Igboro, 2011)

The liquid digestate is harvested every time a continuously fed digester is loaded with new substrate while the digester sludge is recovered whenever the digester is desludged to create a higher effective volume for digestion. (Gas Technology, Inc., 2003)

2.3.1 Biogas

Biogas usually contains about 50 to 70 % CH_4, 30 to 40 % CO_2, and other gases including ammonia, hydrogen sulphide, mercaptans and other noxious gases. It is also saturated with water vapour (Ola, 2008). Biogas burns very well when the CH_4 content is higher than 50 %. It can therefore be used as substitute for kerosene, charcoal and firewood for cooking and lighting. This saves time and money and above all it conserves the natural resources such as cutting trees to get firewood (Fumen and Igboro, 2010)

2.3.2 Digestate

The liquid digestate leaving the digester can be sold as liquid fertilizer because as reported by Mahony, *et al*., (2010) AD does not reduce the NPK content making the digestate more valuable as a fertilizer.

Fischer *et al*., (1984) reported that the concentration of nitrogen, phosphorus, and potassium is generally the same between the manure that has gone through an anaerobic digester and manure that has not. The two major differences are that:

i. More volatile nitrogen is contained in the anaerobically digested manure and
ii. Nutrients are more uniformly distributed in the anaerobically digested manure

The digester sludge (solid digestate) can be post treated aerobically in a process called curing, to produce high quality compost. (Igboro, 2011)

2.4 Design of Anaerobic Digesters

According to Igoni *et al.*, (2008), a preliminary design procedure includes an investigation of the properties of the refuse or MSW with a review to establishing appropriate principles and considerations for the design of the digesters. This, coupled with other relevant information from literature leads to the formulation of the design criteria. The intention is to integrate the technical with economic considerations to form the basis for the design of an anaerobic digester for the production of biogas. Finally comes, scaling of the biogas plant and decisions on materials and methods of construction.

2.4.1 Design Criteria

i. Space availability: this item determines the decision whether the digester is going to be above ground or below ground level, whether the shape is going to be cylindrical or rectangular, whether the orientation will be vertical or horizontal

ii. Existing structures and infrastructures: the use to which existing structures could be put as part of the biogas plant layout is investigated and design is aligned as such. Infrastructures like water and power supply are critical to substrate mixing and waste grinding respectively while drainage and irrigation channels are useful for maintenance and digestate use as plant tonic and soil conditioner

iii. Minimizing costs: this criteria becomes very important when taking a critical look at the return on investment on a biogas plant. The choice of material for its various components as well as design options is affected by their cost outlays.

iv. Available substrates: this determines not only the size and shape of the mixing pit but the digester volume (retention time), the heating and mixing devices and whether additional cost outlay on a grinder will have to be made.

2.4.2 Design considerations

According to Igoni *et al*., (2008), to design a biogas reactor suitable for the biodegradation of MSW with the attendant production of biogas, several factors need to be considered, the main of which are: the type of waste generated, the rate of waste generation and the ambient temperature. These three factors lead to appropriate decisions on the type of digester to be utilized.

2.4.2.1 *Type of digesters*

Igoni *et al*., (2008) gave a description of a variety of digester types that exist for the anaerobic treatment of organic wastes. The selected type will depend on operational factors, including the nature of the waste to be treated especially, its solids content. They noted further that the Oregon State Department of Energy used the solids content of waste to classify digester type into three as follows:

1. Covered lagoon digesters: Suitable for liquid-manure of less than 2 % solids content. This is basically a manure storage lagoon with a cover. The cover traps the gas produced during decomposition

2. Complete-mix digesters: Suitable for manure of 2-10 % solids content. This converts organic waste to biogas in a tank above or below ground with a mechanical or gas mixer to keep the solids in suspension

3. Plug-flow digesters: Suitable for ruminant animal excreta with solid concentration of 11-13 %. A typical design includes a manure collection system, a mixing pit and the digester itself. Addition of water to the waste in the mixing pit adjust the slurry to the optimal consistency before being fed into the digester which is usually

a long rectangular container usually built below grade, with an airtight, expandable cover. New material added at one end pushes older material to the opposite end.

It should be noted here that the type and solid content of the waste being considered in respect of the above mentioned type of digesters were such that the waste are capable of flowing on their own, or forming slurries with water and eventually flowing. The implication is that they could be used in a continuous system. But, MSW is predominantly solid therefore non-flowing. Hence Kahaynian *et al.*, (1991) (cited in Kiely, 1998) suggested the use of "high-solid digesters".

According to Tchobanoglous *et al.*, (1993), continuous-flow digesters, which are by nature low-solid digesters are being used to generate methane from human, animal and agricultural wastes and from the organic fraction of MSW. This process, always requires more water to be added to the waste in order to get it to flow.

In furtherance of this exercise of digester type classification, Vandeberg and Kennedy (1983) and Moletta (1986) highlighted how different anaerobic processes, such as batch, continuous one-stage, and continuous two-stage systems with a variety of methanizers have been applied to the treatment of MSW. Such methanizers include continuously stirred tank reactors (CSTR), tubular reactors, Anaerobic Sequencing Batch Reactors (ASBR), Upflow Anaerobic Sludge Blanket (UASB), and Anaerobic Filters. Based on these developments, Weiland and Rozzi (1991), and Clarck (2001) reported the development of a number of novel reactor designs which have been adapted and developed allowing a significantly higher rate of reaction per unit volume of reactor. Some of these are:

4. Batch Systems: In batch systems, as reported by De Baere, (2000) digesters are filled once with fresh substrates with or without addition of seed materials and allowed to go through all degradation steps sequentially. The hallmark of batch system is the clear separation between a first phase, where acidification proceeds much faster than methanogenesis, and a second phase, where acids are transformed into biogas.

Rajeshwari *et al.*, (1998) reported that anaerobic batch digestion of mixed vegetable waste was carried out successfully at 5% total solids (TS) concentration. Digestion of the waste after 47 days resulted in 0.16 m^3 biogas / kg TS added with a maximum gas production rate on day 26.

In another study, Converti *et al.*, (1999), (cited in Bouallagui *et al.*, (2005)) tested the anaerobic batch digestion of fruits and vegetable wastes (FVW), under both mesophilic and thermophilic conditions with a high rate of digestion. This imrovement in cycle time makes adopting the batch digester system more attractive for the treatment of FVW.

An increase in the TS to 8 % by Bouallagui *et al.*, (2001) and Marouani *et al.*, (2002) showed that the anaerobic treatment in a batch digester was inhibited by the accumulation of volatile fatty acids (VFA) and irreversible decreasing pH problems.

An apt concluding remark on this system is that of De Baere, (2000) that though batch systems have really not succeeded in taking a substantial share of the market in developed economies due to their operational rigiodity, the specific features of batch processes, such as simple design and process control, robustness towards coarse and heavy contaminants, and lower investment costs make them particularly attractive and therefore recommended for developing countries.

5. Anaerobic Sequencing Batch Reactor (ASBR): In an effort to improve on the batch reactor's operational flexibility, Suthaker *et al.*, (1991) emphasised the importance of the application of sequencing batch reactor technology to the anaerobic treatment of MSW particularly FVW. This is characterised by a high degree of process flexibility in terms of cycle time and sequence, no requirement for separate clarifiers, and retention of a higher concentration of slow-growing anaerobic bacteria within the reactor. Research into the ASBR process has been carried out by several other investigators like Dague *et al.*, (1992) and Ruiz *et al.*, (2000). Also, satisfactory high solid content waste degradation and suspended solid removal (90 – 93 %) using the ASBR were recorded by Archana *et al.*, (1999) and Hur *et al.*, (1999).

6. Continuous one-stage systems: Lissens *et al.*, (2001) reported that about 90 % of the full scale plants, currently in use in Europe for the anaerobic digestion of organic fraction of municipal solid wastes (OFMSW) and other bio-wastes, rely on continuous one-stage systems. However, according to Lee *et al.*, (1998), Pavan *et al.*, (2000) and Sachs *et al.*, (2003) a considerable amount of literature has appeared concerning wastes treatment in two phases; first an acid forming phase followed by a methanogenic phase. According to Bouallagui *et al.*, (2005) a likely reason for this discrepancy is that two- and multistage systems (especially using laboratory models) afford the researcher more possibilities to control and investigate the intermediate steps of the digestion process. Industrialists, on the other hand, prefer one-stage systems because of their simpler designs and lower investment costs. Some of the designs in this category include: Fixed dome digesters, floating drum digesters, moving dome digesters, balloon gas holder digesters, etc., with orientation both vertical and horizontal.

Table 2.1 shows the result of different experiments carried out on FVW using anaerobic digestion in different one-stage and two-stage systems.

Table 2.1 Performance data of different anaerobic processes applied for FVW treatment. (Bouallagui *et al*., 2005)

Process	Volume (*l*)	Loading Rate (gVS /(*l*day))	HRT (day)	VS removal (%)	Methane Yield (litre/gVS)	References
Batch System	10	1.06	47	65	0.16	Rajeshwari *et al.*, (1998)
Batch System	5	0.9	32	58	0.26	Bouallagui *et al*., (2001)
Continuous one-stage CSTR	3	1.6	20	88	0.47	Mata-Alvarez *et al*., (1992)
Continuous one-stage CSTR	16	3.6	23	83	0.37	Verier *et al*., (1987)
Continuous tubular reactor	18	2.8	20	76	0.45	Bouallagui *et al*., (2003)
TWO STAGE SYSTEMS						
Solid bed hydrolyser and UASB methaniser	100 & 25	6.8	2.5	94	0.35	Rajeshwari *et al*., (2001)
ASBR hydrolyser and anaerobic filter methaniser	2.5 & 10	4.4	7 + 10	87.5	0.34	Ruynal *et al*., (1998)
CSTR hydrolyser and anaerobic filter methaniser	7 & 4	5.65	2+ 2.3	96	0.42	Bouallagui *et al*., (2003)

In a variant of the continuous-one-stage system, Mata-Alvarez *et al.*,, (1992) examined the performance of the mesophilic one-stage completely stirred reactor (Figure. 2.2) for the treatment of the organic fraction of the wastes coming from a large food market. The organic loading rate (OLR) tested was 1.6kgVS/(m^3 day) using a hydraulic retention time (HRT) of 20 days with a resulting methane yield of about 0.47m^3/kgVS (Table 2.1). In another variant; a semi-continuously mixed tubular digester tested by Bouallagui *et al*., (2003) (Figure. 2.3), the best results (methane yield of 0.45m^3/kgVS) were obtained by applying an OLR of 2.8kgVS/(m^3day), a HRT of 20 days (Table 2.1). In their view, the most significant factor of the tubular reactor, is its ability to separate acidogenesis and methanogenesis longitudinally down the reactor, allowing it to behave as a system of two phases.

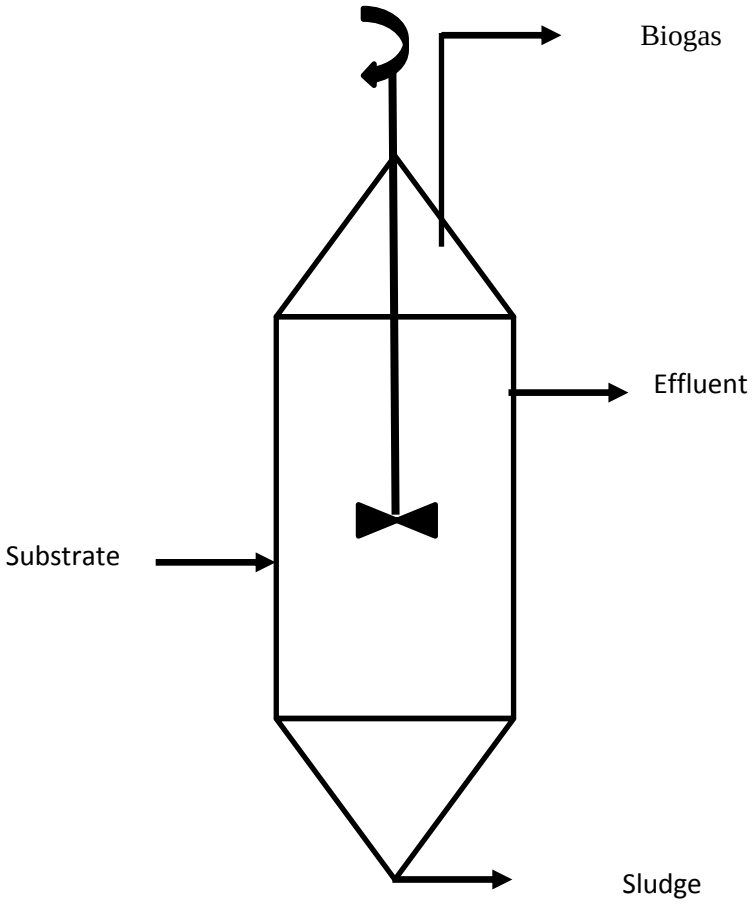


Figure 2.2 Continuously Stirred Tank Reactor (CSTR) (Mata-Alvarez *et al*., 1992)

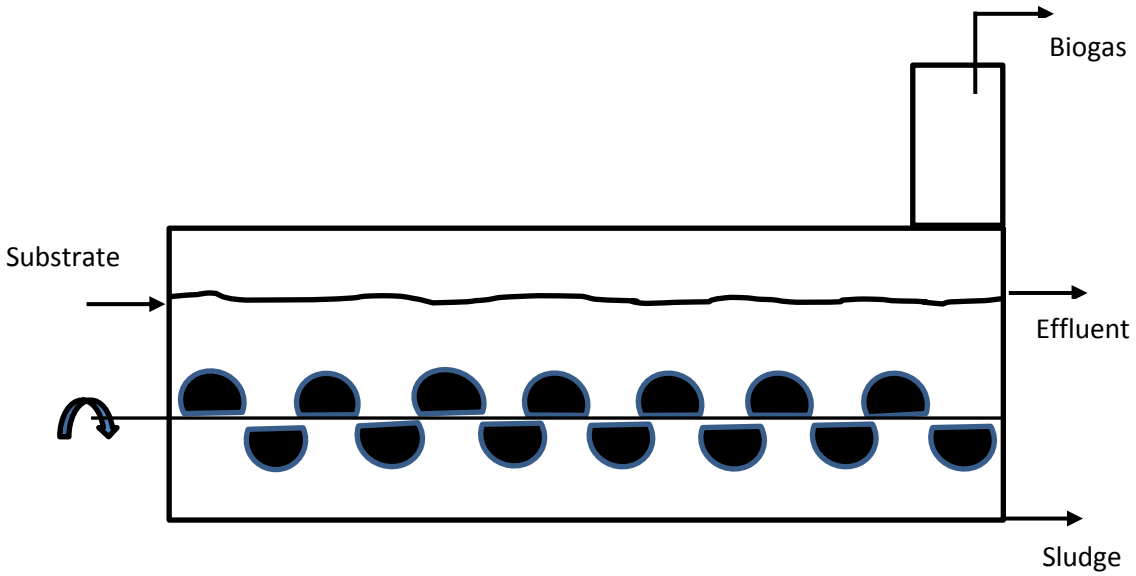


Figure 2.3: Semi-Continuously mixed Tubular Reactor (Bouallagui *et al*., 2003)

7. Continuous two-stage systems: The groups of acidogenic and methanogenic organisms are different with respect to their nutritional requirements, physiology, pH optima, growth, and nutrient uptake kinetics. This characteristic includes their ability to withstand environmental stress factors. Using conventional digestion processes, in which they are combined in one reactor therefore automatically imposes uniform conditions on both groups with the resultant reduction in their efficiency. (Weiland, 1993)

However, Llabres-Luengo and Mata-Alvarez, (1988), posited that a process configuration employing separate reactors for acidification and methanogenesis connected in series, which in effect is a two-phase anaerobic digestion system, allows optimisation of both processes.

This two-step technology was applied in a two-phase anaerobic digestion system experiment conducted by Ruynal *et al*., (1998). The hydrolysis-acidification phase was carried out in an ASBR and methane fermentation was performed in a fixed film reactor (FFR) operated in the upflow mode (Figure 2.4). They were able to report that the global

degradation yield remained above 87 % and the biogas production yield was about 0.29*l*/g of input total COD.

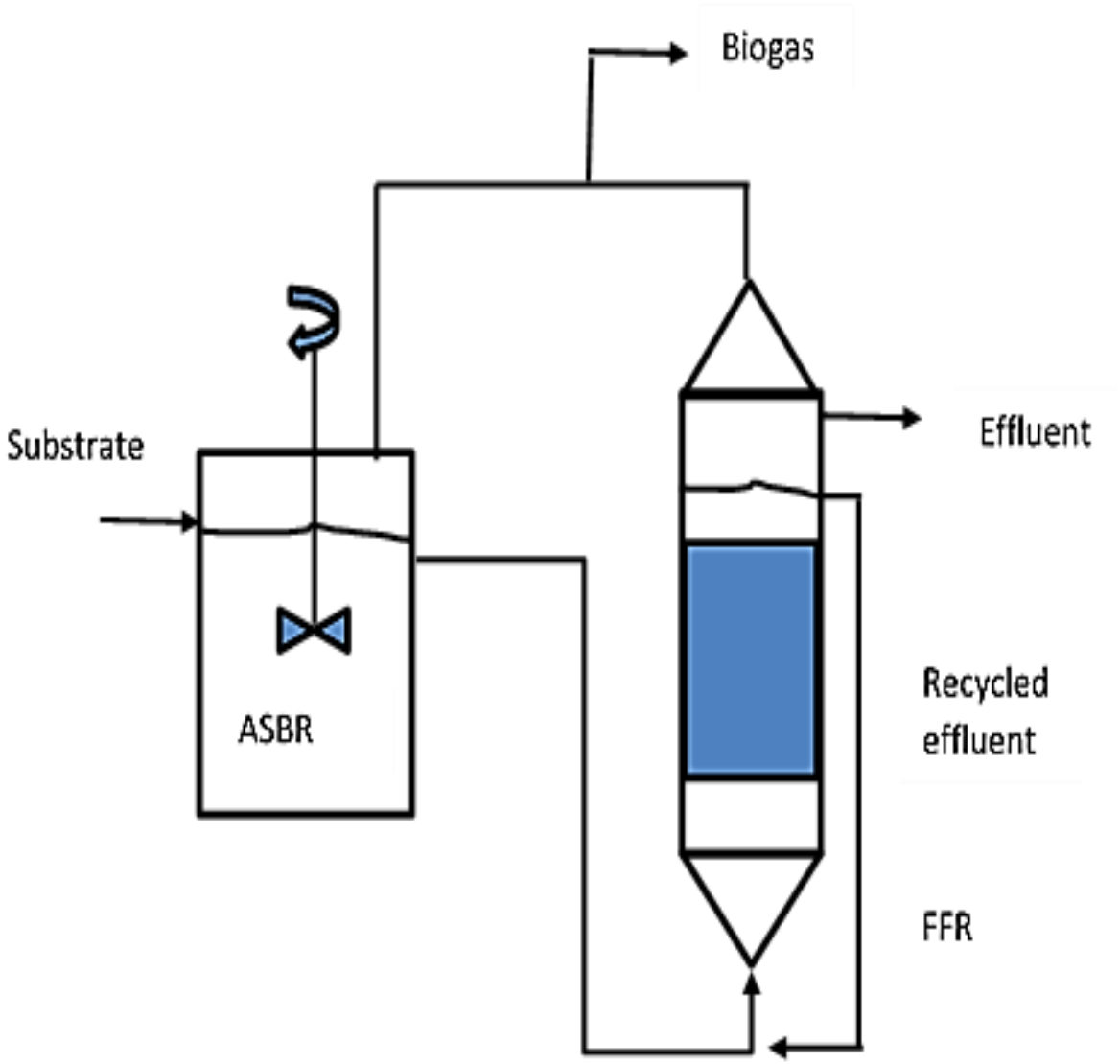


Figure 2.4: Two-phase integrated anaerobic sequencing batch reactor (ASBR) and fixed film reactor (FFR) (Ruynal *et al*., 1998)

In another application, Rajeshwari *et al*., (2001), as illustrated in Figure 2.5 obtained the conversion of over 94 % of vegetable market waste into biogas which supported Bouallagui *et al*., (2005) general conclusion that phase separated digesters may offer the best choice for high efficiency Other performance data of these experiments can be seen in Table 2.1.

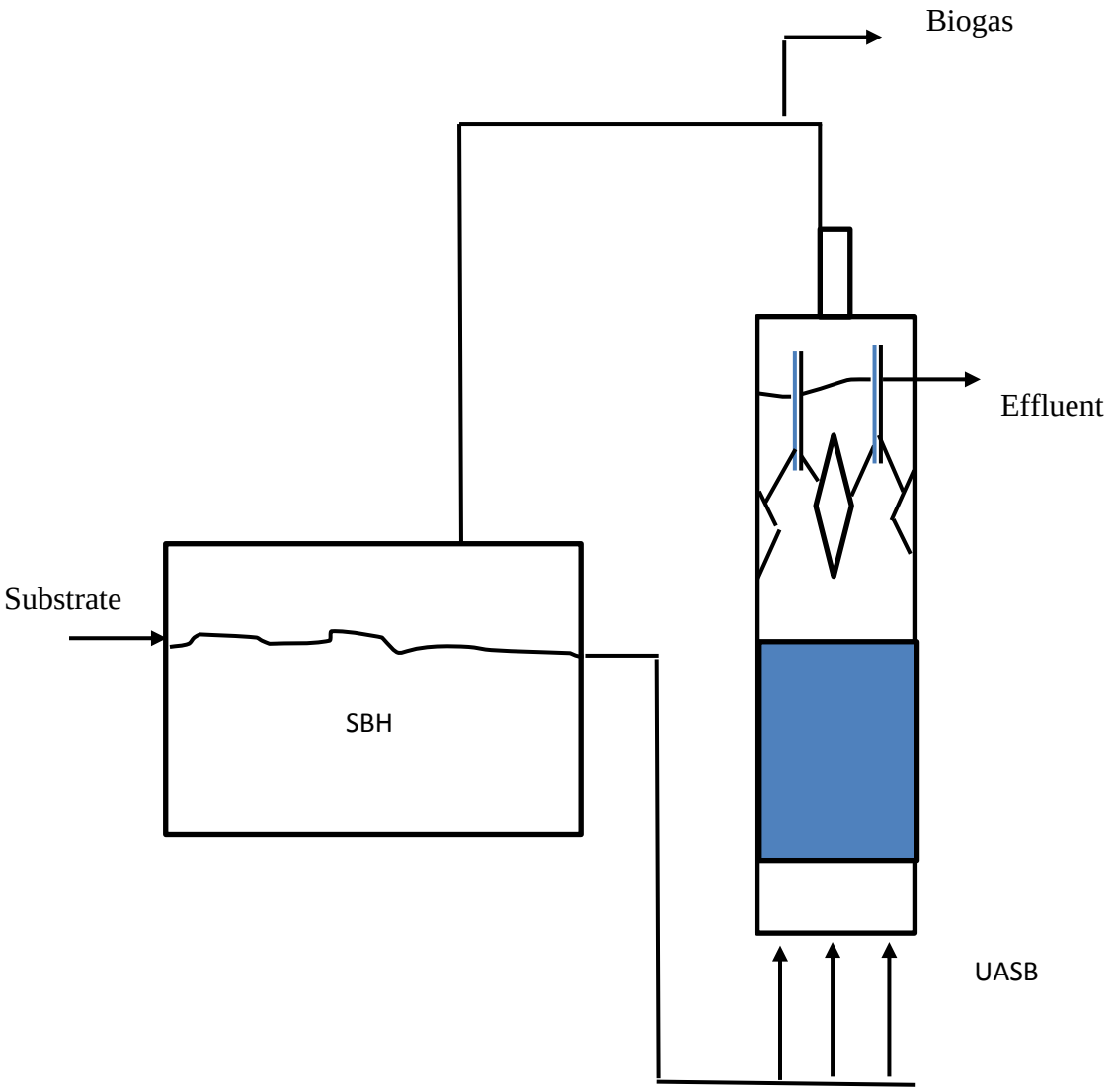


Figure 2.5: Two-Phase Integrated Anaerobic Solid bed hydrolyser (SBH) and Upflow Anaerobic Sludge Blanket (UASB) (Rajeshwari *et al*., 2001)

Other design considerations include

2.4.2.2 *Temperature control*

The rate of decomposition and gas production in an anaerobic digester is sensitive to temperature changes. In general, according to Steadman, (1975), the process becomes more rapid at high temperatures. Tchobanoglous and Burton, (1991) classified the optimal temperature ranges as the mesosphilic (30 - 38^{0}C) and the thermophilic (44 - 57^{0}C) zones. They went on to report that despite the thermophilic benefit in an increased

rate of feedstock consumption and gas production, the digestion becomes increasingly unstable as temperature rises. The system would then require higher rates of heat input but would produce poorer quality supernatants containing higher quantities of dissolved solids. However, Kiely, (1998) insisted that most digesters currently in operation do so at mesophilic temperatures at which good stability and gas production occur while Igoni *et al.*, (2008) reported that reactor temperatures between 25^0c and 35^0c are generally the preferred temperatures to support biological reaction rates and produce a more stable treatment. Igoni *et al.*, (2008) further noted that though choosing the appropriate operating temperature is vital, stabilizing it is even more important. Fortunately for this study, previous research reported by Igboro, (2011) put the average ambient temperature in Samaru, Zaria to be in the range of 22^0C to 30^0C falling within the mesophilic zone.

2.4.2.3 *Hydrogen-ion concentration (pH control)*

The bacteria involved in anaerobic digestion according to Igoni *et al.*, (2008), have a pH range of 6-8 with values close to 7 for optimal activity. They reported that in the initial phase of the process, the production of volatile fatty acids depress the pH, but the reaction of the produced CO_2 in water with hydroxide ions forming HCO_3 (bicarbonate ions), tend to buffer the process pH and restore it to neutrality thus making the process self-regulating. Eckenfelder, (2000) noted that when the rate of acid formation exceeds the rate of its breakdown to methane, process equilibrium is affected and the pH decreases causing gas production to tail off, and the CO_2 content of the gas to increase. The overall effect according to Mattocks, (1984) is the impedance of the whole biogas production process which necessitate sufficient alkalinity to be available at all times up to a level of approximately 3000 mg/l (for sufficient buffering to be maintained), to ensure a high rate of methane production. Eckenfelder, (2000) observed that lime is commonly used to raise the pH. Care must however be taken according to Igoni *et al.*, (2008) to avoid the

precipitation of calcium carbonate through the application of excessive lime. They suggested that, as an alternative, Soda Ash (sodium bicarbonate) can be used for the pH adjustments to overcome this challenge.

2.4.2.4 *Carbon-Nitrogen (C: N) ratio*

Igoni *et al.*, (2008) reported that the concentrations of carbon and nitrogen in the organic fraction of municipal solid waste determine the performance of the anaerobic digestion process because one or the other usually constitutes the limiting factor. Whereas carbon is the energy source for the microbes, nitrogen is needed for growth and multiplication. They went on further to note that the bacteria in the digestion process use up the carbon present 30 to 35 times faster than the rate at which they convert nitrogen. So, for optimal operation, the ratio of carbon to nitrogen should be about 30:1 in the waste raw material. This is in line with Richard, (1998)'s observation that if there is insufficient nitrogen in the waste material, the microbial population will be small resulting in a longer time to decompose the available carbon. Excess nitrogen, beyond the microbial requirement, is often lost from the process as ammonia gas. Richard, (1998) further observed that usually, nitrogen is the limiting element in the processing of MSW. So with the high carbon content of MSW (paper, cardboard, wood, etc.), additives such as manure, clean sewage-sludge (Bio solids), septage and urea are usually required as a supplemental source of nitrogen for ease of digestion.

2.4.2.5 *Moisture content of the waste in the digester*

According to Igoni *et al.*, (2008), moisture is essential for the activities of the waste decomposing anaerobes and hence for effective anaerobic digestion. In line with this, Igoni *et al.*, (2008) reported an experimental digestion of domestic garbage diluted with sewage to a local solids concentration of between 5 and 7 %. They maintained that

stirred-tank digesters can deal with slurries of about 3-10 % total solids (TS), much of which are suspended solids. In their analysis of what they described as "solid feedstock" including green-vegetable mater of about 20 % solids concentration, they explained that if these materials are to be used as feed for a stirred-tank digester, then they will have to be made into slurries. In their final conclusion, a slurry of about 10 % TS is the maximum that can be pumped and piped even if the particle size is small, and 7-8 % may be the maximum which can be handled by smaller pumps and pipelines. This was in consonance with the conclusions of Hobson *et al.*, (1981).

Therefore, moisture content viewed from the total solids content of the waste, according to Oregon State Department of Energy (2002), actually determine the type of digester to be adopted as illustrated in Table 2.2.

Table 2.2: Moisture requirement of different digester types [Oregon state department of energy (2002)]

Digester Type	Total Solids	Water Requirement	Hydraulic Retention Time (days)	Temperature
Covered Lagoon	< 2%	High	35 – 60	Ambient
Fixed film	< 2%	High	2 – 4	Ambient/ Mesophilic
Upflow Anaerobic Sludge Blanket (UASB)	< 5%	High	1 – 2	Mesophilic
Continuously Stirred Tank Reactor (CSTR)	< 10%	Medium	20 - 25	Mesophilic
Plug flow	< 14%	Low	20 - 30	Mesophilic
Batch	10-15%	Low	40-60	Mesophilic

Continuous one-stage; fixed dome	< 10%	Low	25-100	Mesophilic
Continuous one-stage; moving dome	< 10%	Low	25-100	Mesophilic
Continuous one-stage; balloon dome	< 10%	Low	25-100	Mesophilic

2.4.2.6 *Waste particle size*

The particle size of MSW affects the biological transformation of the waste and hence, equipment sizing. For a container filled with particles, reducing the individual particle-size increases the total surface area of the particles in the container. This is desirable for the process operation, as decomposition occurs on the surface of the organic materials. (Richard, 1998). The relatively-large particle sizes of MSW according to Kiely (1998), considerably retard decomposition; hence the necessity for the reduction of the average particle size of the MSW. The particle size reduction can be achieved by shredding, grinding or pulping of the waste feedstock with the ultimate objective of presenting a larger surface area for microbial activity to occur; and hence improve the efficiency of the system. (Agunwamba, 2001)

2.4.2.7 *Mixing*

Mixing is another important operation in achieving optimal anaerobic digestion (Tchobanoglous and Burton, 1991). It is desirable to maintain uniformity of substrate concentration, temperature and other environmental factors as well as prevent scum formation and solids deposition (Agunwamba, 2001). Mixing does not have to take place continuously. It is often better intermittently and may be carried out for just several times a day depending on the type of reactor, the type of agitator used and the total solids content of the feedstock, (Burton and Turner, 2003). To prevent the need for moving

parts within the reactor, the recirculation of biogas through the bottom of the reactor or hydraulic mixing by recirculation of the digestate with a pump can be used to achieve adequate mixing.

2.4.2.8 *Loading rate of organic materials into the digester (OLR)*

The organic loading rate (OLR) represents the amount of volatile solids being fed into the digester each day (Mattocks, 1984). Volatile solids represent that portion of the organic solids that can be digested while the remainder of the solids is fixed. The fixed solids and a portion of the volatile solids are non-biodegradable. The actual loading rate depends on the types of wastes fed into the digester because the types of waste determine the level of biochemical activity that will occur in the digester. The loading rate therefore is very critical to the digester design as it determines the digester volume and indeed the overall process-performance.

It was remarked by Igoni *et al*., (2008) that wide variations in the composition of the incoming flow and the organic loads can upset the balance between acids fermentation and methanogenesis in the anaerobic process. For soluble, easily degradable substrates, such as sugars and soluble starches, the acidogenic reactions can be much faster at high loadings and may increase the reactor's Volatile Fatty Acids (VFA) content and hydrogen concentration thereby, depressing the pH of the system. The loading rates also affect the food to microbes (F: M) ratio according to Kiely, (1988) with the system achieving equilibrium when the food substrates and the microorganism consuming them are in equilibrium.

2.4.2.9 *Pre-treatment of the waste*

Pre-treatment refers to the preparation of the waste for the AD process. According to Ogunmola (1989), MSW (particularly in Nigeria), is a complex mixture of both organic

and inorganic materials. So, because the AD process is for the decomposition of the organic components, it would be preferable to sort the organic from the inorganic. Also, in general, the particle size of the organic fraction of the municipal solids wastes (OFMSW) is such that they will require reduction. These and the other processes that the waste may undergo before being fed into the digester are termed as waste pre-treatment.

2.4.2.10 *Hydraulic retention time (HRT)*

This is the time allowed for the feedstock to stay in the digester. It is also referred to as the residence time (RT). The retention time is determined by the average time is takes for the organic material to digest as measured by the COD and BOD of existing effluents. The longer a substrate is kept under proper reaction conditions the more complete its degradation will be. The rate of the reaction however will decrease with increasing residence time; indicating that there is an optimal time that will achieve the benefits of digestion in a cost effective way. The appropriate retention time depends on the feedstock, the environmental conditions and the intended use of the digestate. Reducing the retention time would reduce the size of the digester, resulting in cost savings. There is therefore an incentive to design systems that can achieve complete digestion in shorter times. A shorter retention time, however, leads to a higher production rate per reactor volume unit but a lower overall waste degradation and poor digestate quality. (Ostream, 2004)

2.4.2.11 *Costs implications in the choice of a digester*

The design considerations for the choice of a biogas plant will not be complete without a critical look at the costs implication of whatever choices are made. In addition to the cost of procuring the components for an anaerobic digester is the cost of Construction and maintenance of the plant, obtaining the feedstock and preparing the MSW for

digestion. According to Ogunbiyi (2001), Process Costs, (i.e. Capital, Operations and Maintenance) are extremely important in selecting the type and size of the reactor.

Igoni *et al*., (2008) noted that the bio-kinetics and design models for the reactor will directly affect the digester's cost, particularly in terms of the digester and feedstock volumes required to yield the desired quantity of gas while for Steadman (1975), the simplest type of methane digester is just a closed container such as a drum, tank or pit in the ground into which the digestible material is loaded. (in short, a batch digester), while, according to the Oregon State Department of Energy (2002), after classifying as three the main types of digesters as; a covered-lagoon, a complete-mix, and a plug-flow digester, the batch digester was the least expensive of the three.

2.4.3 Sizing the biogas plant components

The major components of the biogas plant are as follows:

i. The digester
ii. The gasholder
iii. The mixing equipment
iv. The biogas plant piping
    a. to feed the digester
    b. to discharge effluent from the digester
    c. to safely convey gas out of the gasholder to the point of use
v. The gasholder guide

2.4.3.1 *Sizing the digester*

According to Sasse (1988), definition of certain parameters are required to calculate the size of a digester. The major parameters are

i. Daily fermentation slurry (S_d): The daily fermentation slurry (S_d) is the amount of daily feed material and the mixing water. All feed materials is made up of

a. organic solid/material
b. inorganic solid/material and
c. water

The biogas is produced from the digestion of the organic materials. The inorganic materials (minerals and metals) are unused ballast, which is unaffected by the digestion process. The water content of the biomass and the additional water added to form a slurry allows the methane forming bacteria to be in contact with the organic solid thereby accelerating the digestion process.

So any quantity of biomass (say, municipal solid waste) has x % solid + y % water
For example, fresh cattle manure is made up of 16 % solids and 84 % water. When the cattle dung is mixed with water in the proportion of 1:1. The prepared slurry then has a solids content of 8 % and water content of 92 %. This means that a 20kg slurry of cattle dung and water mixed in equal proportion has

$$\frac{8}{100} \times 20 = 1.6Kg\ organic\ solids\ content$$

S_d (l) = Biomass (l) + Water (l) Equation 2.18

ii. Retention Time (RT): Indicates the period spent by the feed material in the digester. It is appreciably shorter than the total time required for complete digestion of the feed material

$RT = V_d/S_d$ Equation 2.19

Where V_d – Digester volume and S_d – daily fermentation slurry

iii. Specific Gas Production: This represents the gas production of a specific feed material in a specific retention time at specific digester temperature

iv. Dry matter (Dm): The water contents of natural waste material feedstock varies, for this reason, the solids or dry matter content of the feed material is used for exact scientific work.

v. Organic Dry matter or Volatile Solids (Vs)**:** Only the organic or volatile constituent of the feed material are important for the digestion process. Therefore only the organic fraction of the dry matter content is considered.

vi. Digester Loading: The digester loading indicates how much organic material per day has to be supplied to the digester. It is calculated in kilograms of organic dry matter per cubic meter of digester volume per day (kg ODM/m^3/day).

vii. Degree of Digestion: This is measured as a percentage; it indicates the amount of gas obtained as a proportion of total specific gas production. The difference from 100 % indicates the proportion of feed material which is not yet fully digested. In simple biogas plants the degree of digestion is about 50 %; this means that half the feed material is not used

viii. Biological Oxygen Demand (BOD): This is an important parameter in effluent treatment. It indicates the degree of pollution of the effluent, waste or sewage. The BOD is a measure of the amount of oxygen consumed by bacteria in biological purification

ix. Digester volume (V_d): The digester volume V_d is determined by the length of the retention time (RT) and by the amount of fermentation slurry supplied daily S_d. The amount of fermentation slurry consists of the feed material and the mixing water.

V_d (L) = S_d (L /day) x RT (days) Equation 2.20

Where

V_d = Digester volume, (*L*)

S_d = Daily supply of fermentation slurry (*L* /day)

RT = Retention Time, (days)

According to Garcelon and Clark, (2003), the operating volume of the digester should not be more than 90% of the total volume of the digester to allow for the rise of the slurry during fermentation while Sasse (1988) noted that if a biogas plant is loaded not daily but at relatively long intervals, say, weekly, the retention time is correspondingly prolonged.

2.4.3.2 *Sizing the gasholder*

Gasholder volume (V_G): The size of the gasholder, gasholder volume (V_G) depends on gas production and the volume of gas drawn-off. Gas production depends on the amount and nature of the fermentation slurry, digester temperature, and retention time.

Figures 2.6 and 2.7 are curves representing averages of laboratory and empirical values for fresh cattle dung and fresh pig dung. The values vary a wide range owing to differences in solids content of the dung, animal feeds and types of biogas plant used to carry out the experiment. Regular stirring increases gas production. The 26 – 28 ^{0}C line on the curves is a secure basis for scaling the gasholder in the majority of cases.

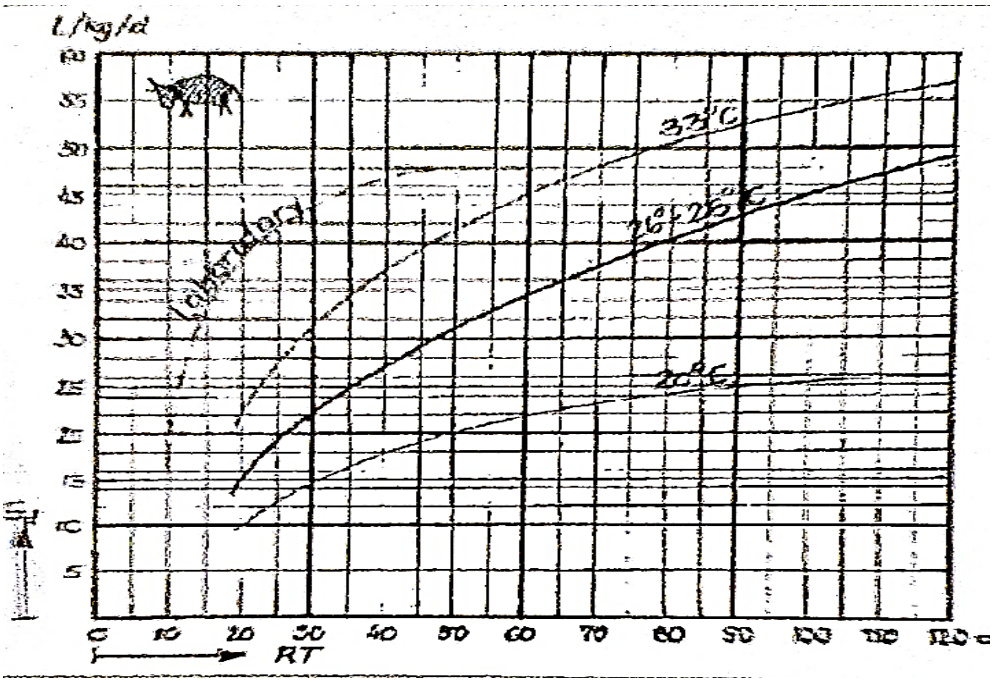


Figure 2.6: Gas production from fresh cattle manure depending on retention time and digester temperature

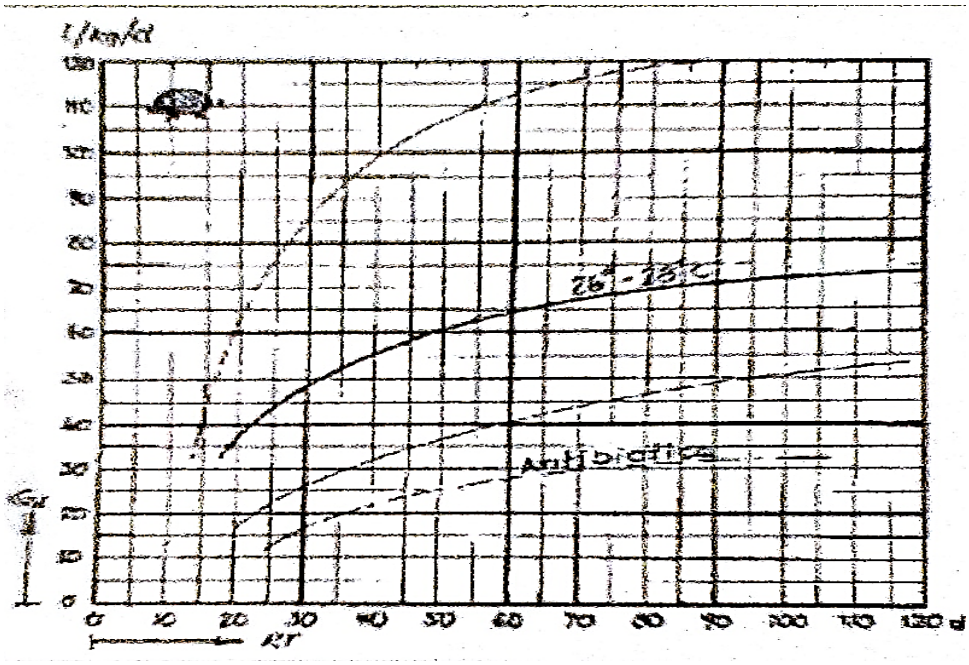


Figure 2.7: Gas production from fresh pig manure depending on retention time and digester temperature

The gasholder should be designed to cover the peak consumption rate for the period of maximum consumption i.e. Gasholder volume (V_{gh})

V_{gh1} = max. gas consumption/hr × max. period for the consumption Equation 2.21

and hold the gas produced during the longest zero consumption period i.e.

V_{gh2} = average gas production/hr × maximum zero consumption time Equation 2.22

The larger value of the two (V_{gh1} or V_{gh2}) determines the size of the gasholder. A safety margin of 10 – 20 % is then added (Igboro, (2011); Kossman *et al*., (2001))

2.4.3.3 *Choosing the mixing equipment*

Although some natural mixing occurs in an anaerobic digester because of rising sludge gas bubbles and the thermal convection currents caused by the addition of heat or temperature differentials during the period, these levels of mixing are not adequate to ensure stable digestion process performance especially at high loading rates. It is therefore necessary that a mixing system be installed to create a homogeneous environment throughout the reactor, so that the digester volume can be fully utilized. Such mixing will lessen temperature stratification, reduce grit settling, and control the formation of a surface scum layer. Further, a proper level of mixing promotes contact between raw sludge and active biomass, and evenly distributes metabolic waste products during the digestion process. (Schlicht, 1999).

What constitutes "adequate mixing" is indeed a difficult question to answer, perhaps the simplest and most direct definition according to WEF, (1987) concentrates upon the main objective of applied mixing, namely that the uniformity of solids concentrations within the digester will be such that any sample taken from any point will not vary by more than 10% from the average of all samples taken, except for deposits on the tank bottom (containing course sand) and floating scum (containing low density material).

Gomez *et al*., (2006) evaluated the anaerobic co-digestion of primary sludge and the fruit and vegetable fraction of the municipal solid wastes under static conditions and with different mixing conditions, with good results being found for the digesters with limited mixing. The co-digestion process was also evaluated at different organic loading rates (OLR) under low mixing conditions, with stable performance being obtained even when the systems were overloaded.

2.4.3.4 *The biogas plant piping*

Martin and Coker, (2016) outlined the choice of pipeworks for biogas piping and safety

a. in feeding the digester
b. in discharging of effluent from the digester and
c. in the conveyance of gas out of the gasholder to the point of use

They reported that the natural gas industry's end-user piping design and regulations serve as guidance for biogas conveyance because both use smaller diameter pipes and operate at lower pressures. The major differences between biogas and natural gas piping systems is the amount of treatment that each gas typically undergoes before conveyance, and the way the piping systems operate. Natural gas pipelines are heavily regulated, inspected and maintained. These regulations fall into two categories: major conveyance piping for distribution, and end-user (after the meter) gas piping. End-user gas piping design and regulations can be used as a comparison to biogas piping because of the similarities — smaller diameter and operating at lower pressures. Major factors to note according to them, in the design of biogas piping are the potential hazards that can occur from

1. Air (oxygen) entrainment: Biogas piping, storage and conveyance systems need to be sized and controlled to avoid pulling a vacuum at any of the vent points within the system. If this occurs, air can get entrained within the biogas system. Biogas produced under sealed conditions is devoid of oxygen and is not explosive because the methane

content is too concentrated to ignite (above the upper explosive limit of 15%). However, once air is entrained the methane content can be diluted within the explosive limit and will contain oxygen, creating conditions that, if exposed to an ignition source, could explode or combust.

2. Flame/spark source: Anaerobic digester tanks, storage systems and landfills require vents to regulate pressure and prevent over pressurization and under pressurization of these systems from the biogas generation and conveyance, pumping, and other activities inherent to these systems. Because of this, there is an envelope around each vent that can contain the appropriate dilution of biogas with the explosive limit (5-15% methane) as well as oxygen. Exposure to a spark source near any of these vents could create an explosive condition. Typical spark sources at digesters are lightning, cigarettes, tools (ideally nonelectrical spark-proof tools), flame torches (used to defrost piping), improperly rated electrical equipment (blowers/compressors/rotating equipment need to be spark-proof) and seal-offs, and even static electricity from clothing

3. Moisture: Biogas is a completely saturated gas when it is released from an anaerobic digester, storage system or landfill. As this gas cools, the moisture condenses within the pipe and must be effectively and safely removed from the piping. If it is not removed, it can pool at low points restricting biogas flow.

4. Corrosion: Biogas contains hydrogen sulfide (H_2S) and mercaptans that can condense in the form of weak sulfuric acid (concentration depends on how much H_2S is in the biogas) within the headspace and piping causing rapid corrosion with incompatible materials. A material compatible with generation of weak sulfuric acid is recommended for any components in contact with biogas

5. Pressure regulation: pressure must be held within the anaerobic reactors, biogas storage and piping systems to prevent release of biogas to the atmosphere and aid in

"pushing" biogas to the use point or conveyance system. This is accomplished using various pressure regulating devices throughout the system, including digester vents, storage system vents, flare system and use points. If any of these fail, an over pressurization event can occur resulting in a release at the weakest point of the system (covers, storage systems, etc.)

6. Leaks: Leaks are mostly from corrosion to piping, gaskets and seals within the system. Periodic sweeping of a biogas system with a gas monitor is recommended to detect any leaks

Other factors to note in biogas piping design and safety according to Ullrich, (2008) are: Material of construction: Plastic pipes are recommended but it is necessary to differentiate PVC, PPR and HDPE. PVC is not resistant against ultraviolet rays. As first priority PPR pipes should be used. The piping should have as little amount of joints as possible.

For long distances HDPE pipes are less expensive. But physical damage can happen easily. It's also difficult to find fittings which are gastight.

Size of pipes: The smaller the diameter of the piping is the higher the decrease of pressure in the pipe. The high pressure of a fixed dome plant (more than 120 cm water column) can compensate this to a certain extent. The bigger the diameter of the pipe is, the better the performance at the consumption points. One size of piping only makes the work easier.

Water traps: The general problem is that warm gas condenses to water in cold pipes. In particular underground piping can condense amounts of water which might lead to blockages or at least to a disturbed gas flow. Occasionally water can be transported to

consumption points, disturbing the cooking or lighting and leading to corrosion. It is therefore critical to install appropriate water traps.

2.4.3.5 The gasholder guide

The gas collection drum in a floating gasholder biogas plant usually has a steel bar framework fixed on its lower inner side, which serves to stir up and break up any scum that is formed, when the drum is rotated using brackets that are fixed on its inclined outer surface. The gas drum is held in a vertical position by a central guide pipe running vertically through a second pipe at its center. This system allows the drum to move up and down and to rotate about its axis, without tipping. The facility of the gas drum to move up and down regulates the pressure of the produced gas at a constant value, while its ability to rotate helps break up any scum formed on the surface of the digester slurry. The floating gas drum biogas system falls in the category of continuous biogas systems, in which the slurry in the digester is displaced into the effluent chamber by incoming slurry. There is need in such types of biogas systems, to ensure that slurry that is fed into digesters is well mixed. (Kuria and Maringa, 2008)

Other variants of this design are necessary in this category of biogas plants.

2.4.4 Safety considerations in the operation of a biogas plant

Igboro, (2011) and Alfa (2013), identified as three the major safety considerations to be considered when working with a biogas system viz: fire/explosion, disease and asphyxiation.

2.4.4.1 *Fire/Explosion*

Methane, the major component of biogas, forms explosive mixtures in air. With this in mind no naked flames should be used in the vicinity of a digester and any installed

electrical equipment in the area must be of appropriate specification and quality. Other sources of sparks like the waste grinding machine must be appropriately shielded. The use of mobile phones in the immediate environment must be avoided. Care should also be taken to avoid introduction of materials that generate a lot of static electricity especially wearing apparel. There are several recorded incidents reports of biogas plant related accidents resulting sometimes in deaths and injuries in Germany, Italy and France by the Bureau for Analysis of Industrial Risks and Pollution (BAPRI) in their Analysis, Research and Information on Accidents (ARIA) database set up since 1999 (comprehensive information can be found at the Bureau's website at http://www.aria.developpement-durable.gouv.fr/), (Delsinne, 2010), in India (Vijayachandran, 2009) and other parts of the world.

2.4.4.2 *Disease*

Anaerobic Digestion is carried out by a mixed population of bacteria of largely unknown origins, from plant and animal wastes. Care should be taken to avoid / minimize direct contact with the digester contents and to wash thoroughly after working around the biogas plant most especially before eating or drinking. Though, the digestion process reduces the number of pathogenic bacteria, the biological nature of the process need to be constantly kept in mind.

2.4.4.3 *Asphyxiation*

Biogas consists mainly of CH_4 and CO_2, with low levels of H_2S and a mixture of other gases. Each of these gases has their challenges to human health, as well as displacement of oxygen.

CH_4 - lighter than air (will collect in roof spaces, etc.), explosive

CO_2 - heavier than air (will collect in sumps, etc.), slightly elevated levels affect respiration rate while higher levels displace oxygen as well.

H_2S - (rotten egg gas) destroys olfactory (smelling) tissues and lungs, becomes odorless as the level increases to dangerous and fatal.

Adequate ventilation, suitable precautions and adequate protective equipment will minimize the dangers associated with biogas handling and use.

2.5 Incinerator System; Definitions, Background and Practices

Incineration as a waste management strategy, is the controlled thermal treatment of residual municipal solid waste by burning, either to reduce its volume or toxicity. (DEFRA, 2013)

Residual Municipal Solid Waste is waste that is household or household like. It comprises household waste, some commercial and industrial wastes e.g. from offices, schools, shops, markets, etc. that are collected by local authorities or private entrepreneurs. The volume of Municipal Solid Wastes can be reduced by more than 90% by this treatment system.

Energy recovery from incineration can be made by utilising the calorific value of the waste to produce heat and/or power. It is therefore not surprising that, Incineration as a treatment strategy for residual MSW is an already proven and bankable technology in most of the developed world; USA, Europe, the United Kingdom (UK), etc., as well as the developing world; Mexico, India, etc. (DEFRA, 2013)

Up to the middle of the last century, in the developed world, incineration was quite common. However, with more restrictive air pollution control requirements necessitating the use of expensive clean-up equipment, the third quarter of the century saw only a number of municipal incinerators in operation comparably. Towards the close of the

century however, increased haul distances to available landfill sites and increased fuel costs have brought about a renewed interest in incineration. (Peavy *et al*., 1985)

To help 'rebrand" them to a reluctant public, modern incinerators are therefore referred to in current times as Energy-from-Waste (EfW) or Waste-to-Energy (WtE) plants. They burn unsorted waste in high-efficiency boilers and energy is produced in the form-of heat, electricity or combined heating and power (CHP). To reduce noxious emissions flue-gas cleaning equipment, e.g. acid scrubbing plant, carbon injection system, electrostatic precipitators or fabric 'type' filters, must be provided, depending on the type of control system employed. The equipment employed for the control of stack emissions can occupy much of the space required by the plant and form a significant proportion of the overall capital costs of the plant (30-60 %). (Walters *et al*., 2007). In the UK for example, all municipal waste incinerator recover energy in the form of electricity and/or heat generation (DEFRA, 2013).

The manual separation of solid waste components is best at the source where the wastes are generated. This is referred to as source sorting. It is actually the most positive way of achieving the much sought after recovery for recycling and reuse of the materials.

Although, incineration on its own is often considered a disposal method, it is in reality a processing method with the current way of looking at it. (Peavy *et al*., 1985). Though, incineration is the term we use, in reality it is simply combustion.

The principal elements of solid waste are Carbon, Hydrogen, Oxygen, Nitrogen and Sulphur. Under ideal conditions, when solid waste is burned the gaseous end products include Carbon dioxide (CO_2), Water vapour (H_2O), Nitrogen dioxide (N_2O), and Sulphur dioxide (SO_2). In practice, however, a variety of other gaseous compounds are also formed depending on the operating conditions under which the process is occurring. [Peavy *et al*., 1985]

Combustion of MSW results in the release of carbon dioxide (and other greenhouse gases). Part of the MSW is biomass derived material e.g. card, paper, timber which is a source of renewable energy. MSW also contains combustible elements which are fossils fuel derived materials e.g. plastics and therefore not a source of renewable energy. Fossil fuel-based carbon dioxide contributes significantly towards the greenhouse effect and hence global warming. In the context of sustainable energy generation, Carbon emitted from biodegradable waste is classed as short cycle Carbon (i.e. the amount given off when combusted equates to that absorbed during its lifetime); hence zero carbon footprint. The growing importance of climate change means the Carbon footprint of waste management needs to be fully considered in selecting waste management technologies. Hence, when considering energy recovery, Carbon emissions need to be considered in terms of composition of the residual waste stream, the type of energy produced and the overall generating efficiency of the facility. (DEFRA, 2013).

Incineration usually involves the combustion of unprepared (raw or residual) MSW. To allow the combustion to take place, a sufficient quantity of Oxygen is required to fully oxidise the waste (which is now considered a fuel due to its potential energy; calorific value). Typically, incineration plant combustion temperatures are in excess of 850^0C and the waste is converted to Carbon dioxide and water. Any non-combustible materials (e.g. metals, glass, etc.,) remain as solid, known as Bottom Ash which contains a small amount of residual Carbon.

2.6 Air requirements for incineration

The most critical item of consideration in combustion is air requirement for the combustion process. (Peavy *et al*., 1985)

To determine the amount of Oxygen required for the complete combustion of solid wastes, it is necessary to compute the Oxygen requirement for the oxidation of Carbon, Hydrogen, and Sulphur contained in the waste. The basic reactions are:

For carbon $C + O_2 \rightarrow CO_2$ Equation 2.23

12g of Carbon requires 32g of Oxygen to burn to produce 44g of Carbon dioxide

For Hydrogen $2H_2 + O_2 \rightarrow 2H_2O$ Equation 2.24

4g of Hydrogen requires 32g of Oxygen to burn to produce 36g of Water vapour

For Sulphur $S + O_2 \rightarrow SO_2$ Equation 2.25

32g of Sulphur requires 32g of Oxygen to burn to produce 64g of Sulphur dioxide

If it is assumed that air contains 23.15 % Oxygen by mass, then the amount of air required for the complete oxidation of 1kg of Carbon is calculated as follows from Equation 2.23:

1 mole of Carbon requires 1 mole of Oxygen for complete combustion to form 1 mole of CO_2

i.e. 12g of C will use 32g of O_2

1 kg of C will therefore use $\frac{32}{12}$ kg of O_2

But 1 kg of air has 0.2315kg of O_2

1 kg of carbon will therefore be completely oxidized by $\frac{32}{12} \times 0.2315$kg of air

= 11.52kg of air

2.7 The components of an incineration plant

Basically, the incineration plant with energy recovery will have the following component parts: (DEFRA, 2013)

- Waste reception and handling

- Combustion Chamber
- Energy recovery plant (out of scope in this study)
- Emission clean-up for combustion gases and
- Bottom ash handling system

It should be noted that most combustibles fed into the incinerator are actually fuel materials with a lot of potential energy (calorific value) stored in them. The biogas therefore only serves as fuel to kick start the combustion process in the incinerator. Once burning commences, adequate aeration ensures complete combustion and attainment of designated combustion chamber temperature.

2.7.1 Waste reception and handling

The characteristic of the waste to be incinerated determines this component of the plant. If the MSW is raw residual waste (i.e. the waste left over after recycling, reuse and removal of the organics for anaerobic digestion and/or composting) or as in some advanced/developed climes used as pre-treated waste feed e.g. refuse derived fuel (RDF), the plant configuration will change accordingly. The waste is normally delivered in bits and pieces and sometimes via a waste collection vehicle and tipped onto a waste reception bay or platform that allows for easy sorting into recyclables, organics and combustibles.

Mixing here is very important for an appropriate blend to allow for consistent feed calorific value-wise into the incinerator. Raw MSW typically has an energy content of about 8 – 11 MJ/kg. Feedstock from source-separated wastes and purely commercial wastes will usually have greater calorific value in the range of 18 – 23 MJ/kg. It is therefore important to ensure a mix of high calorific value materials in the feedstock meant for reduction in the incinerator.

2.7.2 Combustion technology

There are four combustion technologies that are usually employed to burn MSW according to DEFRA (2008)

2.7.2.1 *Moving grate*

In the moving grate furnace system, the waste is slowly propelled through the combustion chamber by a mechanically actuated grate. Waste continuously enters one end of the furnace and ash is continuously discharged at the other end. There are three main sub categories of this system

- The Roller grate: this consists of adjacent drum or rollers located in a steeped formation, with the drums rotating in the direction of the waste movement
- The Steeped inclined grate: this system uses bars, rockers or vibration to move the waste down each of the grates (typically three)
- Inclined counter-rotating grates: grate bars rotate backwards to agitate the waste and prevent it tumbling down the forward inclined grate until burnout is complete.

2.7.2.2 *Fixed grates*

These are typically a series of steps (normally three) with the waste being moved by a series of rams. The first step is a drying stage and initial combustion phase, the second is where the remaining combustion takes place and the third grate is for final carbon burn-out.

2.7.2.3 *Rotary kiln*

Incineration in a rotary kiln is normally a two stage process consisting of a kiln and separate secondary combustion chamber. The kiln is the primary combustion chamber

and is inclined downwards from the feed entry point. The rotation moves the waste through the kiln with a tumbling action which exposes the waste to heat and oxygen.

2.7.2.4 *Fluidised bed*

The combustion of MSW using a fluidised bed (FB) technique involves pre-sorting of MSW material to remove heavy and inert objects, such as metals, prior to processing in the furnace. The waste is then mechanically processed to reduce the particle size. The combustion is normally a single stage process and consist of a lined chamber with a granular bubbling bed of an inert material such as coarse sand/silica or similar bed medium.

2.7.3 Energy recovery

The standard approach for the recovery of energy from the incineration of MSW is to utilise the combustion heat through a boiler to generate steam. Of the total available energy in the waste, up to 80 % can be retrieved in the boiler to produce steam. The steam can be used for the generation of power via a steam turbine and/or used for heating. An energy recovery plant that produces both heat and power is commonly referred to as a Combined Heat and Power (CHP) Plant and this is the most efficient option for utilising recovered energy from waste via a steam boiler.

2.7.4 Emission control for releases to the atmosphere

The emissions limit for specific pollutants that are present in the combustion products (flue gases) from the incineration of MSW are defined in the National Environmental Standards Regulatory and Enforcement Agency (NESREA) Act in Nigeria [FGP, 2007] and the IED/WID in the UK and Europe. An environmental permit via an Environmental Impact Assessment EIA will be required to operate an incinerator fuelled by MSW and

will set-out a range of necessary conditions, including emissions limits for releases to the atmosphere, operating and monitoring requirements.

To meet these limits, the combustion process must be correctly controlled and the flue gases cleaned prior to their final release. The technology supplier for the incinerator plant will define the exact emissions clean-up processes that will be employed to achieve the required standards and utilising Best Available Techniques (BAT).

2.7.5 Bottom ash handling

The main residual material from the incineration of MSW is referred to as "bottom ash" or "Incinerator Bottom Ash" (IBA). This is the residual material in the combustion chamber and consists of the non-combustible constituents of the waste feed. It usually represent about 20 % – 30 % by weight of the original feed waste and only about 10 % by volume. The amount of ash depends on the level of waste pre-treatment prior to entering the incinerator.

2.8 Design of an Incinerator

According to Batterman, (2004), proper design of incinerators should be targeted towards the achievement of

- desired burn-out temperatures;
- residence times and other conditions necessary to destroy pathogens;
- emissions minimization;
- refractory and grating damage avoidance,
- minimisation of fuel consumption,
- adequate aeration for complete combustion and
- ease of loading and removal of bottom ash

The Canadian Council of Ministers for the Environment (CCME), (1989) submitted that right from the conceptual stages of any development, it is necessary to establish a basic design/operating philosophy for the project. In their view, all aspects of the MSW incineration facility should be considered. They insisted that incinerator design must incorporate measures to ensure satisfactory combustion efficiency which can be accomplished if an acceptable combination of temperature, residence time, and gas mixing is achieved in the combustion zone. They noted that temperature generated in the combustion zone is a function of the heating (calorific) values of the waste and the auxiliary fuel, the incinerator design, the air supply, and the combustion control. The actual temperatures achieved depend on heat losses. Heat losses include those from conduction (the transfer of heat through the walls of the incinerator) radiation, and convection losses at the surface, and convection losses due to the exit of the products of combustion and the heating of the incoming air/fuel mixture, the amount of excess air, and the rate of release of energy in the fuel. Although the reaction rates of combustion increase rapidly with higher temperatures, the upper temperature in a system is normally limited by the material used to construct the incinerator. (CCME, 1989)

The effectiveness of the combustion process and to a certain extent, the temperature achieved in the system depend on good mixing of air and fuel in the incinerator. This mixing is usually achieved by ensuring that the air being supplied to the combustion zone has sufficient momentum to penetrate the combustion gases.

Retention time, or the length of time available to ensure complete mixing of air and fuel, is an important incinerator parameter. The incinerator volume also must be large enough to allow fuel and combustible gases to fully mix and burn.

2.8.1 Design criteria for an incinerator

Zinn and Niessen, (1968) outlined the criteria for the design of an incinerator as follows:

i. Easy to operate: In order to insure high quality operation, a minimum of special "techniques" and close attention should be required of the operator. Operators will work on a part-time basis and should not be expected to have a high degree of technical competence.

ii. Wide variety of wastes: An incineration system must be able to handle a wide variety of wastes including wastes of high moisture content. It must also be able to consume a wide variety of waste materials.

iii. Minimal maintenance: the design must ensure that maintenance requirement is minimal

iv. Low cost: in order to justify its use instead of a scavenger for refuse disposal the incineration system should have relatively low cost (both capital and operating costs)

v. Rapid burning: is needed in order to provide a high disposal capacity per square meter of floor area

vi. High combustion efficiency: is required to have good burnout of both the flue gases and residue

vii. Ash residue ease of handling: removal of ash should minimize dusting and contamination of the surrounding area

viii. Easy to light burners and burner stability: the burner unit for combustion units must provide for easy lighting as well as a high degree of flame stability

ix. Minimal external surface temperature: is required for safety and operator comfort.

x. Air pollution control: is necessary to avoid breaking laws and contravening air pollution codes

2.8.2 Design considerations for an incinerator

The following are the major design considerations in the design of an incinerator system

2.8.2.1 *Minimum Temperature*

MSW incinerators should be designed to maintain a temperature high enough to ensure organics destruction. The minimum temperature of 800 – 1200^{0}C should be measured in conjunction with the minimum retention time.

2.8.2.2 *Minimum Retention Time*

MSW incinerators should be designed for a combustion gas residence time of not less than one second at 1000^{0}C or two seconds at 850^{0}C, calculated from the point where most of the combustion has been completed and the incineration temperature has been fully developed. In multi-chamber incinerators, residence time is calculated from the secondary burner(s) flame front or the final secondary air injection point(s). Where the furnace is one continuous space, such as in the single chamber mass burning designs, the location of the complete combustion/fully developed temperature point shall be determined by an overall design review.

2.8.2.3 *Primary Air*

The design should ensure that appropriate air distribution is provided to promote good contact between the burning waste and incoming air.

2.8.2.4 Secondary Air:

A secondary air supply system should be provided to promote mixing and allow for completion of the combustion process. There should be air control capability to be able to adjust for efficiency and also reduce the possibility of quenching the combustion reaction.

2.8.2.5 *Auxiliary Burner*

The auxiliary burner should have sufficient capacity to reach and maintain operating temperature whenever required. The auxiliary burner minimizes emissions by heating up the system before waste is charged to the incinerator and by providing additional heat to complete combustion during upset conditions. It is recommended that the auxiliary burner be capable of providing 60% of the total rated heat capacity.

2.8.2.6 *Maximum Carbon Monoxide level*

Low carbon monoxide levels are an indication of good combustion. To achieve good combustion and low trace organic emissions, the recommended maximum carbon monoxide level for modular and mass burning incinerators is 50ppmdv (57mg/Rm^3) at 11 % oxygen, calculated as a four-hour rolling average.

2.8.2.7 *Air Pollution Control System*

An air pollution control system should be put in place to ensure compliance with the prevailing environmental emission limits and regulations.

2.8.2.8 *Noise Control*

In designing MSW incineration facilities, measures should be taken to control operational noise levels to ensure compliance with local noise by-laws. Operational noise should be limited and at least consistent with ambient levels in the immediate area.

2.8.2.9 *Ash Management*

The residue from an incinerator consist of bottom ash, fly ash and any other solids collected inside the incinerator. The physical and chemical characteristics of these residues must be determined because residue from an incinerator facility may be

hazardous. Adequate precautions should be taken to minimize fugitive emissions during the handling and transfer of incinerator ashes and other solid residues for final disposal.

2.8.2.10 *Monitoring and Control Systems*

A monitoring and control system should be put in place for the whole system from waste feed through combustion to emission control and residue handling and disposal is very important to ensure compliance with laid down rules and regulations guiding the operation of such a facility.

2.8.3 Design considerations for a biogas fuelled incinerator auxiliary burner

According to Fulford, (2010), in order to design an effective biogas fuelled auxiliary burner for use in an incinerator, the following has to be understood and taken into consideration:

2.8.3.1 *Biogas combustion*

Biogas needs to be burned in a burner that is designed for the gas. Since biogas contains roughly 58 % methane and 42 % carbon dioxide, it will not burn properly in a normal natural gas burner. The carbon dioxide content implies that the fuel to air ratio is increased and the flame speed is lower making the flame less stable. (Harrisoz, 2010). Biogas burns in oxygen to give carbon dioxide and water:

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ Equation 2.26

One volume of methane requires two volumes of oxygen, to give one volume of carbon dioxide and two volumes of steam. Since there is 58 % methane in biogas and 21 % oxygen in air:

$\frac{1}{0.58}$ = 1.72 volumes of biogas requires $\frac{2}{0.21}$ = 9.52 volumes of air,

Or: 1 volume of biogas requires $\frac{9.52}{1.72}$ = 5.53 volumes of air or

$\frac{1}{1+5.53}$ = 0.153 = 15.3 % biogas in air (stoichiometric air requirement).

Biogas will burn over a fairly narrow range of mixtures from 9 % to 17 % biogas in air. If the flame is "too rich", has too much fuel, then it will burn badly and incompletely, giving carbon monoxide (which is poisonous) and soot (carbon particles). Burners are usually run "slightly lean", with a small excess of air, to avoid the danger of the flame becoming rich. In most burners, air is mixed with the gas before it is burnt in a flame (pre-aeration). Post-aerated flames, where the gas is ignited at the end of the gas line, give very poor combustion. The amount of "primary air" added to the gas before the flame, varies depending on the design of the burner, but is usually around 50 % of the total air requirement.

2.8.3.2 *Properties of biogas*

The properties of biogas as shown Table 2.3 in must therefore be well understood in order to design a successful biogas burner

Table 2.3: Properties of Biogas assumed 58 % CH_4 and 42 % CO_2, saturated with water vapour at 30^0C, and standard pressure (1bar)

Property	Value	Range
Calorific value (MJ/m^3)	21.5	20.1 to 25.9
Effective Molecular weight	27.35	24 to 29
Density (kg/m^3)	1.0994	0.96 to 1.17
Specific Gravity	0.94	0.82 to 1.00
Viscosity Pa/s	12.97×10^{-6}	
Optimum fuel to air ratio	5.5:1	15 % biogas
Flammability limits	9 % - 17 % biogas in air	
Wobbe Number (MJ/m^3)	22.2	
Burning Velocity (m/s)	0.25m/s in air	

2.8.3.3 *Design equations for a gas burner*

An understanding of the key equations of the Bernoulli's theorem and Prigg's formula and their usefulness in dealing with designing the injector orifice, flames configuration, entrainment, throat sizing, mixing tube length, burner port design for effective cross lighting and to avoid lighting back and flame lift.

2.8.4 Design criteria for a biogas fuelled auxiliary burner

Design criteria were developed by Muson *et al.*, (1990) and Fulford, (2010) as well as necessary equation and relationships for the design of a biogas burner as follows

2.8.4.1 Gas pressure and flow to the burner should conform to Bernoulli's theorem

The force which drives the gas and air into the burner is the pressure of gas in the pipeline. The key relationship between gas pressure and flow is modeled by Bernoulli's equation (assuming incompressible flow) given by:

$$\frac{P}{\rho} + \frac{v2}{2g} + z = \text{constant} \qquad \text{Equation 2.27}$$

where: p is the gas pressure (N m $^{-2}$),

ρ is the gas density (kg m $^{-3}$),

v is the gas velocity (m s $^{-1}$),

g is the acceleration due to gravity (9.81 m s $^{-2}$) and

z is head (m). For a gas, head (z) can be ignored

Bernoulli's theorem essentially states that for an ideal gas flow, the potential energy due to the pressure, plus the kinetic energy due to the velocity of the flow is constant. In practice, with gas flowing through a pipe, Bernoulli's theorem must be modified due to friction. An extra term must be added to allow for energy loss due to friction in the pipe:

$$\frac{P}{\rho} + \frac{v2}{2g} - f\,(\text{losses}) = \text{constant} \qquad \text{Equation 2.28}$$

Using compressible flow theory, gas flow through a nozzle of area A is given by:

$$m = C_d \rho_0 A \sqrt{2\left(\frac{\gamma}{\gamma-1}\right)\frac{P_0}{\rho_0} r^{2/\gamma}\left(1 - r^{(\gamma-1)/\gamma}\right)}$$ Equation 2.29

Where P_0 and ρ_0 are the pressure and density of the gas upstream of the nozzle and $r = P_1 / P_0$, where P_1 is the pressure downstream of the nozzle

2.8.4.2 *Proper design of the Injector orifice or jet for flame stabilization:*

The amount of gas used by a burner is controlled by the size of the gas "jet" or "injector orifice" (an orifice is a hole in a plate). As well as controlling the gas flow rate, the injector has the second important role of separating the burner from the gas supply. It should be impossible for a flame to enter the gas supply pipe.

The gas flow rate (Q) is related to the gas velocity (v) by the area (A) of the pipe through which it is flowing:

$$Q = v A$$ Equation 2.30

For gas flow through an orifice, the area of the hole is not necessarily the area of the flow. A sudden change in flow area causes a "vena contracta", a narrowing of the flow to an area smaller than that of the orifice itself. An empirical version of Bernoulli's theorem is used to define the flow rate and it's given by

$$Q = 0.0467 C_d A_0 \sqrt{\frac{P}{s}}$$ Equation 2.31

(Muson *et al*., (1990))

Where: Q = gas flow rate (m^3/h),

A_0 = area of orifice (mm^2)

p = gas pressure before orifice (mbar)

s = specific gravity of gas

C_d = coefficient of discharge for the orifice.

A graph depicting the relationship is as shown in Figure 2.8

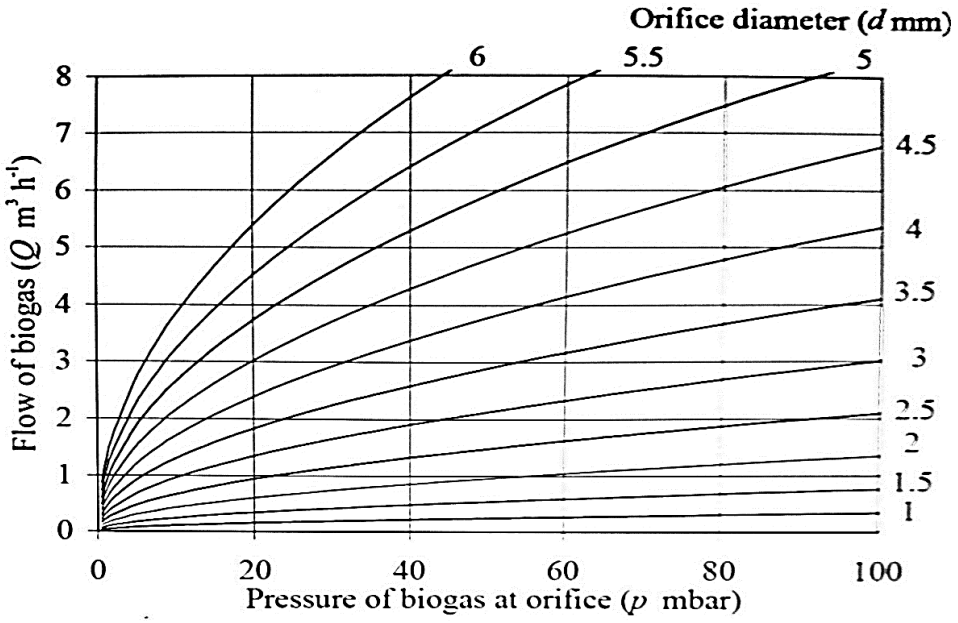


Figure 2.8: Graph of flow rate Q through an orifice where C_d is taken as 0.9.

The coefficient of discharge for the orifice takes into account the vena contractor and friction losses through the orifice. It usually has a value between 0.85 and 0.95.

To maximize C_d, the angle (a) of approach before the orifice should be 30° and the length of the orifice channel (b) should be between 1.5 and 2 times the orifice diameter (c) as illustrated in Figure 2.9

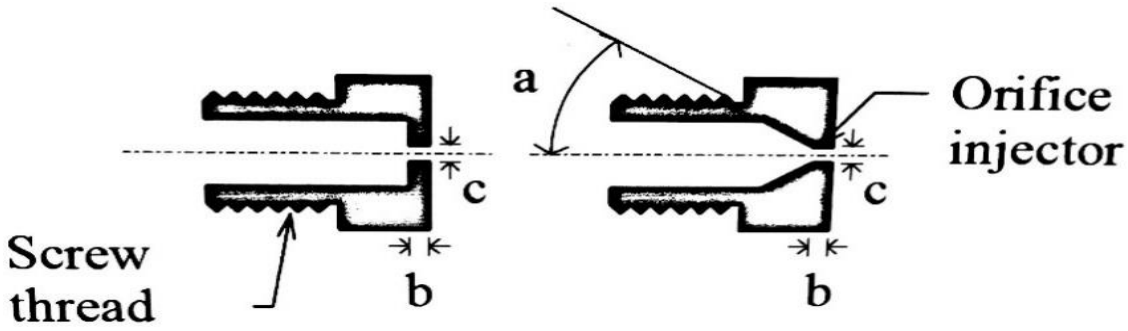


Figure 2.9: Orifice configurations

As gas comes out of the injector, air is "entrained" into the stream through holes in the biogas-air mixer and is mixed in the pipe and mixing port with the gas before it comes

out of the burner port. The unburned gas is heated up in an "inner cone" and starts burning at the "flame front" (Figure 2.10). The cone shape is a result of laminar flow in a cylindrical mixing tube, the mixture at the centre of the tube is moving at a higher velocity than that at the outside. The main "combustion zone" is where the gas burns in the primary air and generates the heat in the flame. The "Outer mantle" of the flame is where combustion is completed with the aid of the secondary air that is drawn into the flame from the sides. The combustion products (carbon dioxide and steam) are at a high temperature, so rise vertically away from the flame, transferring heat to the air close to the top of the flame. It is this air moving vertically away that draws in the cooler secondary air to the base of the flame. The size of the inner cone depends on the primary aeration. A high proportion of primary air makes the flame much smaller and concentrated, giving higher flame temperature.

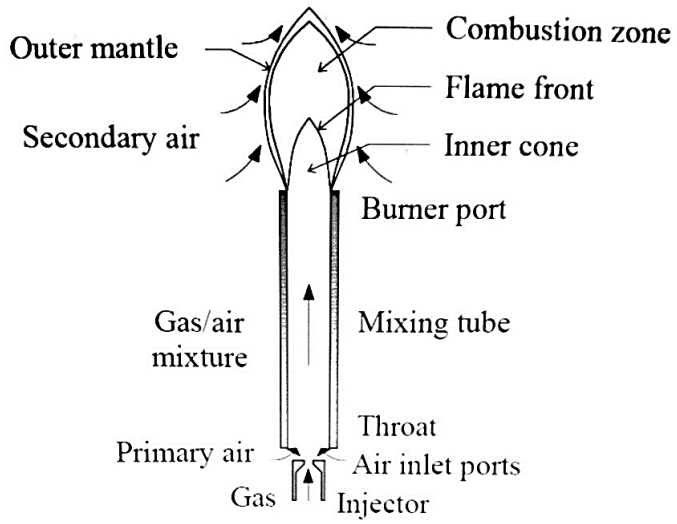


Figure 2.10: Flames configuration

The gas emerging from the injector enters the end of the mixing tube in a region called the "throat". The throat has a much larger diameter than the injector, so the velocity of the gas stream is much reduced.

The velocity (V_0) of the gas in the injector orifice is given by:

$V_0 = \frac{Q}{3.6\times10^{-3}A_0}$ m/s Equation 2.32

with Q in m^3/h and A_0 in mm^2, while velocity in the throat is reduced to:

$V_t = V_0\frac{A_0}{A_t} = V_0\frac{d_0^2}{d_t^2}$ Equation 2.33

Ignoring the vena contractor and friction.

The gas pressure just after the nozzle then becomes:

$P_t = P_0 - \rho\frac{v_0^2}{2g}[1-(\frac{d_0}{d_t})^4]$ Equation 2.34

(Muson *et al*., (1990))

The value of P_0 is around atmospheric pressure, as the throat is open to the air, so this drop in pressure is sufficient to draw primary air in through the air inlet ports to mix with the gas in the mixing port.

The primary aeration depends on the "entrainment ratio" (*r*), which is determined by the area of the throat and the injector:

$r = \sqrt{s}\,[\sqrt{\frac{A_t}{A_0}} - 1] = \sqrt{s}\,[\frac{d_t}{d_0} - 1]$ Equation 2.35

Equation 2.35 is referred to as Prigg's formula

where A_t and d_t are the area and diameter of the throat and A_0 and d_0 are the area and diameter of the injector.

Prigg's formula holds if the total flame port area (A_p) is between 1.5 and 2.2 times the area of the throat. This ratio is approximately independent of the gas pressure and the flow rate. The primary air supply is rarely enough to give a stoichiometric mixture.

2.8.4.3 *Appropriate throat and mixing tube design to allow for adequate biogas-air mix*

The flow rate of the mixture in the throat (Q_m) is then given by:

$Q_m = \frac{Q(1-r)}{3600}$ with *Q m* in m^3/s and *Q* in m^3/h Equation 2.36

(Muson *et al*., (1990))

The pressure drop due to the flow of the mixture down the mixing tube should be checked, by first calculating the Reynolds number:

$$\text{Re} = \frac{\rho d_t v_t}{\mu} = \frac{\rho d_t}{\mu} \frac{4Q_m}{\pi d_t^2} = \frac{4\rho}{\pi\mu} \frac{Q_m}{d_t} \qquad \text{Equation 2.37}$$

Where ρ and μ are the density and viscosity for the mixture

(Use ρ = 1.15 kg/m^3 and μ = 1.71×10^{-5} Pa at 30°C).

The pressure drop (Δp) is then given by:

$$\Delta p = \frac{f}{2} \rho v_t^2 \frac{L_m}{d_t} = \frac{f}{2} \rho \frac{16 Q_m^2}{\pi^2 d_t^5} L_m \qquad \text{Equation 2.38}$$

Where $f = \frac{64}{Re}$, when $\text{Re} < 2000$ and $f = \frac{0.316}{Re^{1/4}}$, when $\text{Re} > 2000$

The pressure drop should be much less than the driving pressure.

Most burners are designed to have a throat that gives an aeration greater than optimum, with a device for restricting the air flow, so the optimum aeration can be set for a given situation. For a cylindrical throat, the mixing tube must be long enough to allow good mixing of the gas and air. A throat length (L_t) of 10 × d_t is usually recommended.

$$L_t = 10 \times d_t \qquad \text{Equation 2.39}$$

Where d_t is the diameter of the pipe conveying the biogas to the burner

$$d_t = \{\frac{r}{\sqrt{s}} + 1\}\, d_o \qquad \text{Equation 2.40}$$

d_o is the hole drilled for air to enter for the necessary Biogas-Air mixture required for biogas to burn in air and r is the entrainment ratio

Diameter of orifice, (d_o)

$$d_o = \sqrt{\frac{Q}{0.036 C_d}} \text{ x } 4\sqrt{\frac{S}{P}} \qquad \text{Equation 2.41}$$

2.8.4.4 *Burner ports design for flame stability and cross lighting while avoiding lighting back and flame lift:*

The big advantage of a gas burner is that the heat can be directed to where it is needed, by designing the burner properly. However, the design must allow for particular problems that can occur when burning gas, especially biogas. Such problems like lighting back where it is possible for the flame at a burner port to travel back down the mixing tube to the injector. The way to overcome lighting back is to choose a burner port size smaller than a certain size. For ports in thin metal, this will be 2.5 mm diameter for natural gas. If the burner port is drilled in thicker metal, then it can be larger. Because biogas has such a low flame speed, lighting back is not usually a problem. 5 mm diameter holes in 5 mm thick metal do not seem to light back. The other challenge is "flame lift" which is an opposite effect to lighting back and is a real problem with biogas with the flame lifting off the burner port as illustrated in Figure 2.11

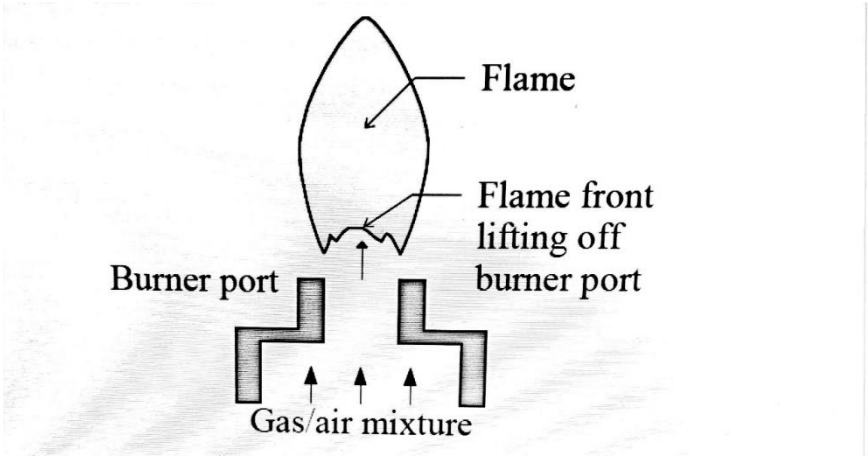


Figure 2.11: Flame lift phenomenon in a gas burner

The flame lifts off from the port and can "blow off" and go out. "Flame lift" occurs when the speed of the gas/air mixture through the burner port is higher than the speed of the flame burning in the gas. Biogas has a stoichiometric flame speed of only 0.25 m/s so the total flame port area must be chosen so that the mixture velocity through the ports is

much lower than this figure. The flame velocity at the flame front is likely to be 50% of the stoichiometric value, as the flame is not fully aerated at this point.

Even if the burner port size is designed correctly for a particular situation, a variation in conditions can result in flame lift. Alterations in the entrainment ratio, caused by adjustments in the primary air controls, or by partial blockage of the air inlets by dirt, can cause the flame velocity at the flame front to change. Increased supply pressure will increase the mixture flow rate and velocity, also causing flame lift.

The mixture supply velocity (v_p) is given by

$v_p = \frac{Q_m}{A_p} \ll 0.25$ m/s, Equation 2.42

with Qm = $\frac{Q(1+r)}{3600}$ in m^3/s, Equation 2.43

and A_p, the total burner port area in m^2, = $n_p\frac{\pi d_t^2}{4}$ Equation 2.44

where: n_p is the number of ports, each of diameter d_p in m.

The flow of the gas/air mixture through each of the burner ports must be uniform, so each burner port should be of the same size. Also the pressure drop in the supply pipes leading to the burner ports must be of the same value. The usual way to ensure this is to use a manifold that is symmetrical and with a cross-sectional area that is much larger than the total flame port area.

For a bar burner, with the flame ports arranged in line on a cylindrical or rectangular tube, it is common to place the mixing tube so the mixture comes out at the centre of the manifold. Baffles may be required to balance the flow patterns within the manifold, so the flame size is uniform. Burner ports are often round in shape, but can be made any shape.

The total area of the burner ports is limited by the need to prevent flame lift. It can also be defined by the heat output from the burner ports, which should be less than 900 W/cm^2 (0.09 W/m^2) of burner port area. The size and positioning of the individual burner ports are defined by various factors, such as the heat pattern required, the need for burner ports to be close enough together for cross-lighting and the need for an adequate supply of secondary air.

Domestic stoves, used mainly for cooking, usually have burner ports arranged in a circular pattern, as most cooking pots have a circular base. The size of the circle depends on the average size of the cooking pots to be used.

As for cross-lighting, a burner is usually lit at one place, so the flames should jump from one burner port to the next for the whole burner to light. Also the flames at individual burner ports may go out, making cross-lighting essential. For biogas, the gaps between burner ports should be around 5 mm to ensure cross-lighting occurs.

2.8.4.5 *Materials of construction*

Gas burner components are usually made of cast metal, as they must take high temperatures, be very robust and withstand corrosion. Many parts can be made from aluminium, except for those parts which might reach temperatures above its softening point (600°C). Cast iron is used for parts that reach higher temperatures, as it is fairly resistant to corrosion. However, it is brittle and can shatter if dropped onto a hard surface. Mild steel can take high temperatures, is not brittle, is easily welded and is very strong, so can be used for many components. However steel is susceptible to corrosion so must be coated with a corrosion inhibitor that can withstand the temperature in which the steel is being used. (Fulford, 2010)

2.9 Operation of Incinerators

The most important operational consideration in the operation of an incinerator according to DEFRA (2010), is compliance of any chosen incineration technology with prevailing emission standards. In the UK for instance, all waste incineration plant must comply with the Waste Incineration Directive (WID) 2000 and the Industrial Emission Directive (IED) (Directive 2010/75/EU). This Directive sets the most stringent emissions controls for any thermal processes regulated in the European Union (EU). The objectives of the IED are to "Reduce emissions into air, soil, water and land and to prevent the generation of waste, in order to achieve a high level of protection of the environment taken as a whole".

In Nigeria, the Federal Ministry of Environment (FMOE) through NESREA and their counterparts in the various states of the federation are responsible for regulation and compliance of Waste Disposal, Incineration and Emission Standards with objectives similar to that of the UK/EU IED.

The key requirements in the IED for the operation of an incineration plant are:

i. A minimum combustion temperature and residence time of the resulting combustion products. For MSW, this is a minimum requirement of 850^0C for 2 seconds;
ii. Specific emission limits are set for the release to the atmosphere of various combustion products (Table 2.4)
iii. A requirement that the resulting bottom ashes and slag produced has a Total Organic Carbon (TOC) of less than 3%. (EC, 2006)

The combustion conditions are required to ensure that complete burnout of the waste is achieved while the emission limits to atmosphere are set to minimise any environmental

and health impacts. The carbon content in the ash represents minimisation of the combustible material and destruction of waste.

2.9.1 Emission standards and compliance matters

In the findings of an assessment of small scale incinerators for the World Health Organisation (WHO), Batterman (2004), concluded that it is not recommended for WHO to develop or specify emission standards or guidelines for small scale incinerators. Such standards he pointed out, will require quantitative emission limits on each type of pollutants and standards require the use of inspection, testing, monitoring and certification programs for such incinerators and their operators to ensure compliance. He believe, small scale, low cost incinerators will not be able to meet modern emission standards for many pollutants and possibly several toxic metals. To meet emission standards, incinerators must be designed to use air pollution control equipment (removing particles, acid gases, etc.), combustion process monitoring (temperature, flow rates, etc.), and process controls (waste, fuel, air flows). Few of these technologies are adaptable to small scale low cost incinerators that do not have exhaust fans, pollution controls, dampers, monitoring, electrical power, etc. These technologies will greatly increase the cost and complexity of the incinerators, and they are unlikely to perform reliably in many settings given the need for careful operation, regular maintenance, and skilled operators. He therefore recommended the use of the following measures as an alternative to ensure effective waste treatment, minimize emissions, exposure and risk to workers as well as the community:

1. The use of approved incinerator designs that can achieve appropriate combustion conditions (e.g. minimum temperature of 800^0C, minimum chimney heights relative to surrounding structures);

2. Appropriate siting practices (e.g. away from populated areas or where food is grown);

3. Adequate operator training (including both classroom and practical training);

4. Appropriate waste segregation, storage and ash disposal facilities;

5. Adequate equipment maintenance;

6. Managerial support and supervision;

7. Sufficient budgeting by management authority to ensure compliance with the aforementioned measures. [Batterman, 2004]

Finally, to conclude on this section, it should be noted that municipal solids waste incineration is on the mandatory list of projects that, up to year 1999, required an Environmental Impact Assessment (EIA) "No Objection" certificate from the Federal Environmental Protection Agency (FEPA) according to Decree 86 of 1992 (FRNOG, (1992)) before they were merged into the Federal Ministry of Environmental by virtue of the Presidential Directive Ref. No SGF 5/5/221 of October 12, 1999. (Fagbohun, 2002). Later, their duties were taken over by the National Environmental Standards and Regulations Enforcement Agency (NESREA) under the NESREA (Establishment) Act, 2007, No. 25.

Table 2.4: Air Emission Limit Values (Directive 2000/76/EC) (Annexure V)

ITEM	DAILY AVERAGE VALUES	VALUES	UNIT
1	Total Dust	10	mg/m^3
2	Total Organic Carbon (TOC)	10	mg/m^3
3	Hydrogen Chloride (HCl)	10	mg/m^3
4	Hydrogen Fluoride (HF)	1	mg/m^3
5	Sulphur Dioxide (SO_2)	50	mg/m^3
6	Nitrogen Monoxide (NO) and Nitrogen Dioxide (NO_2) for existing incineration hour or new incineration plants	200	mg/m^3
7	Nitrogen Monoxide (NO) and Nitrogen Dioxide (NO_2) for existing incineration plants with a nominal capacity of 6 tonnes per hour or less	400	mg/m^3
8	Dioxins and Furans (total conc. Calculated using the concept of toxic equivalence in accordance with Annex I)	0.1	ng/m^3
9	Carbon Monoxide (CO)	50	mg/m^3
10	Heavy Metals (values applicable to Incinerators treating HAZARDOUS WASTES ONLY)	0.05	Mg/m^3

2.9.2 Exposure, safety and health risks from incineration

Batterman, (2004), reported that exposure to risks from incineration could be direct and indirect. Direct exposure for the operators and the immediate surroundings and indirect exposure pathways from air pollutants emission from incineration. These pathways may include for example consumption of locally produced, meat, eggs and dairy products, consumption of fish from local waterways that are contaminated by air pollutants, and dermal contact with contaminated soils. These pathways are important for persistent pollutants that can bio-accumulate into food, a result of the deposition of toxic emissions onto plants and soil with subsequent ingestion by farm animals or in the case of fish contamination, from deposition directly into water bodies or onto soil and runoff into surface waters with subsequent uptake in fish. Indirect exposure pathways can therefore be very important for dioxins, furans and other emissions if:

1. Food is grown near the incinerator,
2. Animals are raised on fields near the incinerator,
3. Lakes, ponds, or other surface drinking water sources have a local catchment area,
4. Subsistence fishers, or farmers in the area obtain most of their food from local sources,
5. Children play in the dirt subjected to significant atmospheric deposition

Several studies have examined human exposures and risks from incinerator emissions. Most have looked at municipal or hazardous waste incinerators. Few validation studies have been completed. As a result of stricter emission standards in the EU and the USA, releases of these substances have been significantly reduced in several countries (WHO, 1999), and concentrations in many types of food (including mother's milk) have decreased sharply (UNEP, 1999)

Domingo, (2002) shows effects of decreasing stack gas concentrations emitted from a municipal solid waste incinerator in Montcada, Spain from approx. 10 ng TEQ/m^3 to below 0.1 ng TEQ/m^3 (air pollution control devices added included acid gas scrubbing, fabric filtration, and activated carbon) that reduced environmental exposures from 0.051 to 0.012 pg TEQ/kg-day for adults, and from 0.081 to 0.027 pg TEQ/kg-day for children, based on measured soil and plant concentrations measured 500m from the incinerator, and modelling inhalation, dermal contact, and incidental soil and dust ingestion. Other dietary pathways were excluded as vegetables, grains, fruits, cereals and livestock were not raised in the urban area.

Other studies of note include Nouwen *et al*., (2001) and Bennett *et al*., (2002). Both measured the individual intake fraction or iFi for dioxins (and other compounds). The iFi is defined as that fraction of the emissions taken in by a specific individual over all exposure pathways. Thus, the iFi represents the source-to-dose transfer coefficient that accounts for dispersion, transformations, bioaccumulation, etc. Bennett *et al*., (2002) arrived, based on the CalTOX model, at an iFi value of 2.1 x 10^{-12}. This value it should be noted, represent a time and space average over the United States of America (USA) and not values that might apply to a highly exposed individual. On the other hand, Nouwen *et al*., (2001) estimated exposures near two large municipal incinerators near Antwerp, Belgium for several scenarios, including one assuming high consumption rates of locally produced foods, e.g. 25 % of vegetables, 50 % of meat, and 100 % of milk. For this scenario, Year 1980 exposures with high emissions (18.9 g TEQ/yr) were 2.8 and 11.3 pg TEQ/kg-day for adults and children, respectively, most coming from milk and meat ingestion. Due to air pollution controls (lowering emissions to 3.1 g TEQ/yr), Year 1997 exposures were 0.73 and 2.4 pg TEQ/kg-day for adults and children, respectively. From the total TEQ emissions reported in the paper, the local individual intake fraction

iFi was derived. Specifically, the adult iFi was 1.0×10^{-9}, and the child iFi was 1.8×10^{-8} (based on averaging estimates for Years 1980 and 1997). It should be noted that these values are 150 and 520 times greater than that derived by Bennett *et al*., (2002), but they apply for an exposed population (within approx. 3 km of the incinerators).

2.9.3 Safety Risks in the operation of a small scale incinerator

Russel, (2000) outlined the following safety notes that must be carefully adhered to in the operation of an incinerator:

1. When opening the loading door it is advisable to always wear eye protection and a face mask. Opening the loading door during operation mean that additional air will enter the combustion chamber. This may cause blowback to occur and the flame to flare up out of the loading door. The blow-back does not last long but it could cause injury to anyone standing too close to the incinerator.
2. The operator should not open the door while standing at the front of the incinerator door. The loading door is designed so that it hinges from the front of the incinerator and opens towards the operator. This provides the operator with some protection from any blowback and keeps him/her away from the opening to the combustion chamber.
3. The operator should wait a few moments to allow any blow-back to die down before loading waste materials into the incinerator.
4. It is important to watch out for small explosions as some waste materials such as ampoules (for medical wastes) and glass bottles possibly containing liquids and medicines may explode during incineration causing glass and other waste materials to be blown into the atmosphere. The operator should ensure that eye protection and a facemask is worn when opening the loading door or when visually checking the

combustion process through the air inlet or when opening the ash door while the incinerator is in use.

5. In handling solid waste, it is necessary to always wear heavy-duty gloves and apron most especially while handling medical solid waste. If the waste is bagged, the bag should be held by the top and away from the body. The bag should be dropped through the loading door opening and if it gets stuck, a stick should be used to push it into the combustion chamber. If the waste is loose, a shovel should be used to load it into the combustion chamber.

6. In removing ash and other solids from the combustion chamber, the ash or other waste materials should never be handled by hand. A stick or scraper should be used to pull the solids out through the ash door and into a dustpan or box.

7. The bottom ash or other waste materials should not be removed from the combustion chamber until they have cooled down. This will take about five hours. If the incinerator is in operation on a daily basis then the ashes and other waste material can be removed the following day as part of the preparation for operation.

8. The bottom ash and other waste materials should be disposed carefully by burying or placing in a skip for disposal by local authority or other authorised disposal company in case of medical waste.

2.9.4 Health Risks in the siting and operation of incinerators

To determine the health risk from incineration in a particular environment, according to Batterman, (2004), the Health Risk Assessment (HRA) framework should be known. The objective of HRA is to estimate effects of incinerator emissions, in this case, air pollutants, on human health, including short-term acute impacts (systemic diseases) and chronic (long-term) impacts (e.g., cancer). The goal generally is to assess the overall risk associated with exposure to emissions, e.g., the 'risk' quantified as the probability of

harm, the fraction of the population potentially affected, and/or the number of cases of disease. Historically, health concerns raised by incineration is usually focused on communities living near the incinerator. However, more recently and rather definitively, the National Research Council (NRC) identified three potentially exposed populations (NRC, 1999):

1. the local population, which is exposed primarily through inhalation of airborne emissions;
2. workers at the facility, especially those who clean and maintain the pollution control devices; and
3. the larger regional population, who may be remote from any particular incinerator, but who consume food potentially contaminated by one or more incinerators and other combustion sources that release persistent and bio-accumulative pollutants.

The analysis will follow the general steps of hazard assessment, toxicity assessment, exposure assessment, and risk characterization while the assessment is typically, screening, in nature.

2.9.5 Hazard assessment in the siting and operation of incinerators

In hazard assessment, causative agents are identified and the feasibility of linkages and mechanisms between air pollutants and adverse health effects are demonstrated.

Dose-response assessment

The dose-response assessment describes the toxicity of the chemicals identified using models based on human (including clinical and epidemiologic approaches), and animal studies. Dose-response relationships depend on the pollutants, which could be systemic, carcinogens or conventional pollutants. For systemic toxicants, many studies have indicated a threshold or 'no-effect' level, that is, an exposure level where no adverse

effects are observed in test populations, as cell mechanisms are able to repair or isolate damaged cells. Some health impacts may be reversible once the chemical insult is removed. In this case, a reference dose or concentration, for use in the risk characterization as a component of the hazard index is established. For carcinogens, both linear and nonlinear dose-response models are used. With linear models, doubling the exposure doubles the predicted risk. Cancer potencies are typically provided for each exposure pathway or for total intake. For conventional pollutants, e.g., particulate matter and SO_2, dose-response relationships for morbidity and mortality are often derived using epidemiological studies. All in all according to Batterman, (2004), the end result of all the analyses should be to emphasize and mitigate against those agents that are judged to cause most of the risks and human health impacts.

2.10 By-Products of Municipal Solid Waste Treatment Systems

Anaerobic digestion of municipal solid waste generates a wide range of useful byproducts.

Biogas is used to generate electricity and as fuel for a lot of applications like cooking, heating, drying, and incineration

Liquid digestate is used as fertilizer and as soil conditioner

Undigested biomass (referred to as digestate solids, fiber or biofiber) contained in the solid effluent of anaerobic digesters provides opportunities for value-added byproducts. Organic fertilizer, livestock bedding, compost, fuel pellets, and construction material (medium density fiberboard and fiber/plastic composite materials) are a few examples of value-added byproducts that could be created from digestate solids (Kirk and Gould, 2016)

2.10.1 Fertilizer value of digester effluent; liquid digestate and sludge

Igboro, (2011) from experiments conducted at ABU concluded that digester sludge can be used to make compost rich in plant nutrients and when cured for twenty days supported plant growth and serve as soil conditioner. This is in conformity with Kotcharkorn *et al*., (2004) report that digester sludge are rich sources of plant nutrients. He went on further to report that while Brain (1998) found out that potatoes and grasses grown on digester effluent had better yield than those grown on fresh farmyard manure or balanced with organic fertilizer (NPK). Meanwhile, Magem, (1995) reported that application of digester effluents to potted plant as fertilizer resulted in their death.

2.10.2 Fertilizer value of wood ash

One of the traditional agricultural practices in Nigeria is bush burning after land clearing. A lot of wood ash is thereby produced. Calcium is the most abundant nutrient averaging almost 20 % of the ash. It has been shown that ash can therefore be used to raise soil pH, just as agricultural lime is used. Compared to calcium, other nutrients are present in much smaller amounts. Wood ash has about four percent potassium, and less than two percent phosphorus, magnesium, aluminium and sodium. The small amounts of these nutrients is the reason that ash is considered a "low grade" fertilizer. In terms of commercial fertilizer, average wood ash would be about N:P:K 0:1:3. (Griffin, 2006)

2.10.3 Soil pH and nutrient availability

According to Igboro (2011), soil pH is an important chemical property because it affects the availability of nutrients to plants and the activity of microorganisms. Figure 2.12 gives a general indication of these relationships.

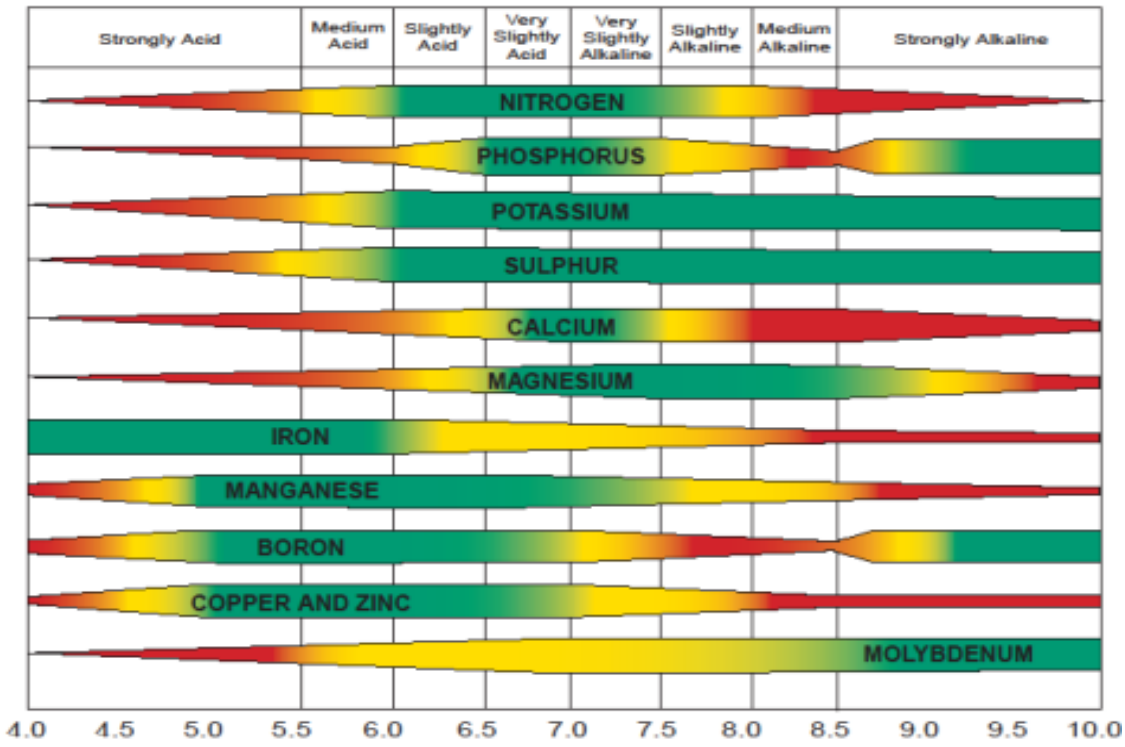


Figure 2.12: pH scale and Nutrient Availability Chart (Verdegaal Brothers Inc., 2007)

2.11 Review of previous similar research in the WREE dept, ABU, Zaria

Several research has been carried out in the department of Water Resources and Environmental Engineering, ABU, Zaria. This current effort is an effort to develop on the previous works

2.11.1 Production of biogas and compost from cow dung in Zaria, Nigeria

Igboro, (2011) carried out a study to produce biogas and compost (soil conditioner) from cow dung. A fixed dome digester and moving gas holder collection system was designed and fabricated using locally available materials to digest cow dung from National Agricultural Products Research Institute (NAPRI) and Zango abattoir respectively.

A batch digestion system was used with the introduction separately each time from each source 90kg of fresh cow dung collected overnight into the digester with water to form a slurry in a ratio 1:1 by volume. The gas is collected from the digester through a 20mm

diameter flexible hose connected to the bottom of the gas collection system allowing it to pass through water as a scrubber into a cylindrical gasholder floating in the water jacket. The daily gas production was determined from the rise in level of the calibrated gasholder. A total of 0.05m^3/kg of biogas was produced from the abattoir waste, while the three types of waste from NAPRI produced 0.03m^3/kg, 0.014m^3/kg and 0.03m^3/kg of biogas respectively. The average temperature observed during the study was within the mesophilic temperature range (20 – 40^{0}C)

After the 40 day period of digestion, the sludge was removed from the digester, dewatered and allowed to cure for 20 days before being used on trial plots to grow maize and guinea corn with improved yields compared to baseline plots without any treatment. A biogas stove was fabricated using locally available materials and used to boil water with a biogas consumption rate of 0.006m^3/min.

2.11.2 Comparative evaluation of biogas production from various substrates

Alfa, (2013) carried out this study to produce biogas from cow dung, chicken droppings and lemon grass as well as the respective co-digestion of cow dung and chicken droppings with lemon grass. 25 litre digesters and gas collection systems were fabricated and used to digest the substrates singly as well as in co digestion. For the single substrates the total volume of gas produced were 0.032m^3/kg, 0.035m^3/kg and 0.021m^3/kg before scrubbing and 0.021m^3/kg, 0.022m^3/kg and 0.015m^3/kg after scrubbing for cow dung, chicken droppings and lemon grass respectively. For the co-digested substrates, cow dung + lemon grass produced 0.024m^3/kg before scrubbing and 0.017m^3/kg after scrubbing while chicken droppings + lemon grass produced 0.032m^3/kg before scrubbing and 0.021m^3/kg after scrubbing. The average ambient temperatures during the study were within the mesophilic range (20 – 40^{0}C). The pH values were stable and always in the optimal range between 6.5 – 8.0. The reduction in solids were 75.3 %, 60.1 %. 98.2 %,

61.9 % and 35 % for cow dung, chicken droppings, lemon grass, cow dung + lemon grass, and chicken droppings + lemon grass respectively. The total coliform contents of the residue were 2.00 x 10^7 CFU/100ml, 6.00 x 10^7 CFU/100ml, 1.00 x 10^7 CFU/100ml and 1.00 x 10^7 CFU/100ml for cow dung, chicken droppings, cow dung + lemon grass, and chicken droppings + lemon grass respectively with 95 %, 70 %, 95 % and 99 % reduction in each case. Pathogens such as *Salmonella spp.* and *Klebsiella spp*. were still present in the residue although *E. Coli* and *Shigella spp*. were removed. The estimated methane contents of the gas from cow dung, chicken droppings, lemon grass, cow dung + lemon grass and chicken droppings + lemon grass were 65.59 %, 61.71 %, 71.95 %, 68.53 % and 66 % respectively. The cooking rates for water were 0.079L/min, 0.070L/min, 0.067L/min, 0.064L/min and 0.060L/min for unscrubbed biogas from lemon grass, cow dung + lemon grass, chicken droppings + lemon grass, cow dung and chicken droppings respectively while those for scrubbed biogas from lemon grass, cow dung + lemon grass, chicken droppings + lemon grass, cow dung and chicken droppings were 0.12L/min, 0.10L/min, 0.091L/min, 0.085L/min and 0.079L/min respectively. The rice cooking rates were 0.0038kg/min, 0.0034kg/min, 0.0033kg/min, 0.0031kg/min, and 0.0030kg/min for unscrubbed biogas from lemon grass, cow dung+ lemongrass, chicken droppings + lemon grass, cow dung and chicken droppings respectively while those for scrubbed biogas from lemon grass, cow dung+ lemongrass, chicken droppings + lemon grass, cow dung and chicken droppings were 0.0055kg/min, 0.0048kg/min, 0.0045kg/min, 0.0041kg/min and 0.0039kg/min respectively.

CHAPTER THREE

MATERIALS AND METHODS

In order to determine the methodology for this study it is necessary to first decide on the proposed size of waste treatment systems to be installed. The size of the biogas plant is dependent on the maximum gas consumption requirement of the burner for the incinerator system. The material for both treatment system depends on the chosen methodology.

3.0 Materials

3.1.1 Materials for the biogas plant

Once the sizes of the digester tank and biogas holder as well as the material is known, sizing the other components and decision on materials hinged on this initial choice.

The following materials were therefore used for this study:

a) 2000 litres black GP® vertical cylindrical plastic water storage tank was used for the digester

b) 1500 litres black GP® vertical cylindrical plastic water storage tank was used for the gasholder

c) 20mm uPVC pipe, valve and fittings was used for biogas conveyance externally out of the digester base through a 25mm Tigre® backnut

d) 25mm Tigre® Plastic pipes and fittings was used for biogas conveyance internally out of the digester base Tigre® backnut

e) 50mm uPVC pipes, valves and fittings was used for loading, discharge and draining the digester

f) 50mm Tigre® backnuts was used for digester loading at 100mm from the base, digester discharge 1400mm from the base, and draining at the centre of digester base.

g) Plastic funnel was used for weekly substrate loading

h) Standard tailors PVC measuring tape (1500mm long) was glued to the gasholder for measurement of gasholder lift above the substrate to calculate volume of gas produced

i) Hakkam-B Solid Waste Crusher (22KW combination screw / hammer mill. An adaptation of the "Kwarankwatsa" designed and fabricated by Hakkam-B in Ibadan, Nigeria for wet milling in Zamfara State. Patent pending) was used to reduce the particle size of the organic fraction of the municipal solid waste and greens for easy digestion in the AD

j) Hand held pH meter (Made in England) was used for the daily measurement of digester pH

k) Stainless steel buckets (10 litre size) was used for mixing and weighing of slurry before loading into the digester

l) Weighing scale (Made in China) was used to measure weight of weekly substrate loading into the digester

m) Stainless steel sieve buckets (5 litre size x 3mm slot. Fabricated at Zaria Pan-taker market) was used for screening slurry before loading into the digester to avoid blockage

n) 50 litre plastic drums was used for collection and mixing of ruminant intestinal waste from the abattoir and grinding from the waste grinder

o) Thermometers (G.H. Zeal London. Made in England) was used to collect daily temperatures of the digester as well as ambient temperature of Samaru, Zaria

p) Personnel Protective Equipment (surgical gloves, nose mask, coverall, rain boots, eye protector glasses) were used during grinding, mixing and loading of waste into digester

q) 50mm steel belt with bolt and nut clamp and guiding brackets was used to control gasholder movement along the guide frame

r) 50mm diameter galvanised iron pipe was used to construct the gasholder guide frame

s) A site was acquired close to the WREE department on which the biogas plant was installed as shown in Plate IV and V.



Plate IV: Solid waste crusher/grinder installed for processing the substrate



Plate V: Biogas plant set up

3.1.2 Materials for Laboratory work

a) Spectrophotometer (CECIL Instrument. Cambridge, England) was used for the determination of Phosphate, Sulphate, Nitrate, Potassium and Total Organic Carbon.

b) Burettes (50ml. Technico-Glass 'B' BS846BC20^0. Made in England) was used for the determination of Phosphate, Sulphate, Nitrate, Potassium and Total Organic Carbon.

c) Conical flask (Pyrex. Made in England) was used for the determination of Phosphate, Sulphate, Nitrate, Potassium and Total Organic Carbon.

d) Pipettes (10ml Precicolor (HBG). Made in Germany) was used for the determination of Phosphate, Sulphate, Nitrate, Potassium and Total Organic Carbon.

e) Beakers (250ml. Technico-Glass 'B' BS846BC20^0. Made in England) was used for experiment to determine the energy content of biogas

f) Bunsen burner was used to determine the energy content of biogas

g) Ring stand was used to determine the energy content of biogas

h) Glass rod was used to determine the energy content of biogas

i) Laboratory weighing scale was used to determine the energy content of biogas

j) Thermometers (G.H. Zeal London. Made in England) was used to determine the energy content of biogas

k) Tripod Stand was used in the determination of the energy content of biogas

l) Plate VI shows the set up for the Laboratory determination of the energy content of the biogas



Plate VI: Laboratory set up to determine the energy content of the biogas as fuel

3.1.3 Materials for the Incinerator

a) Burnt hollowed clay bricks were used for the incinerator body and grating lining to hold the waste

b) Local red lateritic clay was used to construct incinerator domed roof

c) Mild steel pipe (DN100) was used as exhaust pipe to convey combustion gases out of the combustion chamber

d) Biogas Burner was constructed in mild steel pipe configured to cover the surface area of the grating and allowance was made for placement of the burnt hollowed clay bricks within the burner construction

e) Non-electric Air extractor fan was installed on exhaust pipe to extract combustion gases out of the combustion chamber

f) Sandcrete blocks was used to build incinerator base and bottom ash collection compartment

g) Cement and sand was used for joining clay bricks.

h) Gravel: was used to screed floor for waste reception and handling bay

i) Mild steel sheet and square pipes: was used to construct the Bottom Ash compartment and incinerator waste loading door.

j) Mild steel rod (DN12.5) was used to construct grating to hold refractory blocks for incinerator floor to accommodate easy bottom ash collection.

k) Biogas – Air mixer was designed for the burner to ensure complete combustion in the chamber.

l) Air blower was used to improve air circulation for complete combustion.

m) Galvanised iron pipes (DN15) was used to construct the air injection pipeworks.

n) Reinforced polyethylene flexible hose and clips was used to convey biogas from biogas plant to incinerator.

o) Brass ball valves (DN 15) were used to control biogas flow from biogas plant to incinerator.

p) Personnel Protective Equipment (hand gloves, face protector, gas mask, and furnace protective gear) was used while operating incinerator.

q) Mild steel Pipes (DN50) was used as pole to hold incinerator rain protective roof.

r) Zinc roofing sheets: were used as rain protective cover for the incinerator dome.

s) Gas lighter (Long nosed type) was used to light the biogas burners.

t) Long handled rake: was used to turn combustion chamber contents.

u) Scrapper: was used to remove bottom ash from the ash compartment.

v) Mild steel Tray was used to pack the bottom ash

w) Mild steel safety box was used to remove the bottom ash for further disposal.

x) A site was acquired close to the WREE department on which the incinerator system was constructed as shown in Plate VII and VIII



Plate VII: Incinerator set up



Plate VIII: The Combined Biogas Plant and Incinerator System set up at ABU, Zaria

3.2 Methods

3.2.1 Design of the biogas plant and Incinerator system

The design of this combined MSW treatment system could be approached from the available waste characteristics or the need for the production of a specific volume of biogas to operate the incinerator. This design was based on the later.

3.2.2 Design of the digester

The digester volume V_d (from Equation 2.20) is determined by the length of the retention time (RT) and by the amount of fermentation slurry supplied daily S_d. The amount of fermentation slurry consists of the feed material and the mixing water.

V_D (*l*) = S_d (*l* /day) x RT (days)

Where V_d = Digester volume, (*L*)

S_d = Daily supply of fermentation slurry (*L* /day)

RT = Retention Time, (days)

For a known digester size and specific RT, the daily amount of feed is given by

S_d (*L*/day) = V_d (L) / RT (days).

For example using a Retention Time (RT) of 50 days and a digester volume of 1600 litres in Equation 3.2 gives 1600 = S_d x 50. S_d = 1600/50 = 32 litres. Fresh Cattle dung is made up of 16 % solids content + 84 % water. To obtain a feedstock with a VS content of 8% (for easy flow) it is necessary to dilute further by mixing 32 litres of dung + 32 litres of water to give 64 litres of feed stock with 8% VS content.

Meanwhile, 16% solids content in the 32 litres of dung gives 5.12 litres of solid with a density of 400g/*l* and therefore a weight of 2048g VS

Likewise, at a density of 400g/l, the slurry will have a weight of 400g/*l* x 64*l* = 25,600g

At 8 % VS, this gives 8/100 x 25600 = 2048g VS

At 50 days RT and 26-28^{0}c on the gas production curve (Figure 2.6)

1kg of cow dung produces 30 litres of biogas daily

2.048 kg will give 30 x 2.048 = 61.44 Litres of biogas daily.

However, the choice of retention time chosen for the design will also depend on the use to which the biogas is to be put and the convenient frequency of loading the digester. In this case, it is more convenient to load per week and the logistics involved dictated an economic decision in favour of an approximate production of 60 litres of biogas daily hence the choice of an RT of 50 days. The first 5 - 10 days gas production is usually discharged to waste because it is mostly carbon dioxide and will not have enough methane to flame. It is estimated the plant should be able to produce an estimated 420 litres of methane rich biogas per week thereafter.

2000 litres GP plastic tank with effective volume of 1600 litres of digester contents can be charged as follows:

e.g. 800 litres of solid waste + 800 litres of water = 1600 litres of slurry

For this project a RT of 50 days shall be used and daily slurry of 64 litres shall be adopted. This should produce an estimated biogas in excess of 60 litres/day. Exact production shall be confirmed through daily measurements of gas holder lift above the digester biomass.

3.2.3 Design of the gasholder

The size of the gasholder, gasholder volume (V_{gh}) depends on gas production (V_{gh2}) and the volume of gas drawn-off for use during combustion (V_{gh1}). Gas production depends on the amount and nature of the fermentation slurry, digester temperature, and retention time.

1600 litres of slurry at 8% VS contains to 128litres solids content which at 400g/l density is 51,200g of solids or 51.2kg which at 30*l*/kg of cow dung is equivalent to 1536 litres of

biogas. At a RT of 50 days this gas production works out to an average of 1536/50 = 30 *l*/day or 1.28 *l*/h = 0.00128m^3/h (V_{gh2})

The proposed biogas burner complete with the biogas – air mixer is projected to consume about 500 – 600 litres of biogas/hr i.e. 0.5 – 0.6m^3/h. For this study, let the maximum gas consumption/hr be 0.6m^3/h (V_{gh1}).

For the purpose of this work let the time of maximum consumption be 2hr

Also, let the time of maximum zero consumption be the interval of one week =168hr

Applying Equations 2.21 and 2.22. The gasholder volume V_{gh} can be calculated as

$V_{gh} \geq V_{gh1}$ or V_{gh2} + 10% (V_{gh1} or V_{gh2})

Equation 2.21 - V_{gh1} = max. gas consumption/hr × max. period for the consumption

Equation 2.22 - V_{gh2} = average gas production/hr × maximum zero consumption time

The larger value of the two (V_{gh1} or V_{gh2}) determines the size of the gasholder.

A safety margin of 10 – 20 % is then added

V_{gh1} = 0.6 m^3/h × 2hr = 1.2m^3

V_{gh2} = 0.00128m^3/h × 168hr = 0.215m^3

Therefore, gasholder volume $V_{gh} \geq$ 1.2 + 0.12 or 1.32m^3 say, 1.5m^3.

The incinerator auxiliary burner is projected to consume about 500 to 600 litres of biogas per hour of operation. To be able to operate the incinerator for a burn cycle of two hours will therefore require a gasholder of 1200 litres capacity. Allowing for a factor of safety of 25% gives a gasholder capacity of 1500litres matching the calculated value of V_{gh}.

3.2.4 Construction of the biogas plant

The digester was made out of a 2000 litre standard GP vertical Cylindrical Plastic Water Storage Tank commonly found in the market while the Gasholder was made from a 1500 Litre version of the same product as shown in Plate V. A solid waste crusher/grinder as shown in Plate IV was installed to reduce the particulate size of the solid waste for a more efficient anaerobic bacterial degradation action. The method of construction was as described step by step in Table 3.1 which shows the calculation for the digester, gasholder and other components of the biogas plant including their specifications, materials and methods description

Table 3.1 Biogas Plant Components, Materials Specifications and Methods Description

Component	Materials	Design and Dimensioning	Output Data	Methods, Implications & Remarks
Digester	Plastic Cylindrical Vertical Tank Colour: black	Standard Size: 2000 litres Diameter: 1190mm Total Height: 1700mm Effective height H_E: 1550mm Effective Volume $\boldsymbol{V = \frac{\pi d^2}{4}}$ H_E = ($\pi \times 1.19^2 \times 1.55$)/4 = 1724 litres. Operating volume ≤ 90% Effective volume = 0.9 x 1724 = 1552 litres Operating height of Biomass in Digester Tank $H_O = \frac{1.552 \times 4}{\pi \times 1.190^2}$ H_O =1400mm	Effective Digester Volume V ≤1724L Operating Volume=1552L Biomass depth= 1400mm	The top of the tank was cut off to achieve H_E which determines the height of the Biomass feed pipe (**Legend Id. No. 3)** while the value of H_O determines the height of the digestate outlet **(Legend Id. No. 4)** on the digester tank
Gasholder	Plastic cylindrical Vertical Tank Colour: black	Standard Size: 1500 litres Diameter: 1095mm Total Height: 1500mm Effective height H_E: 1380mm. Effective volume $\boldsymbol{V = \frac{\pi d^2}{4}H}$ = ($\pi \times 1.095^2 \times 1.38$)/4 = 1299 litres. Operating volume ≤ 95% of Total volume = 0.95 x 1299 = 1234 litres	Effective Gasholder Volume ≤ 1299L Operating height H_{OG} =1311mm or 131cm on the level measuring tape on the tank	The output dimensions for the digester and the gasholder tank determine the height of the gasholder guide frame **Legend Id. No. 12**

		Operating height H = $\frac{1.234\times4}{\pi\times1.095^2}$ mm H_{OG} =1311mm (131cm)		
Biomass Feed Pipe	uPVC pipes and fittings	Size = 50mm diameter Length of the uprising PVC pipe ≥ H_E = 1550mm	Length of uprising pvc pipe = 1550mm. Backnut installed on digester tank at 100mm to the base.	The fittings installed in order, from the digester tank outwards are: backnut, nipple adaptor, 100mm long pipe, ball valve, 100mm long pipe, union connector, 100mm long pipe, 90^0 bend, 1550mm long uprising pvc pipe, 90^0 bend, 100mm long pipe, 90^0 bend. The ball valve and union connector were installed for ease of maintenance
Digestate outlet pipe	uPVC pipes and fittings	Size = 50mm diameter	Length of uprising pvc pipe = 600mm. Backnut is installed on digester tank at 700mm to the base.	The fittings installed in order, from the digester tank outwards are: backnut, nipple adaptor, 100mm long pvc pipe, ball valve, 100mm long pvc pipe to reach the guide frame, nipple adaptor, threaded tee, threaded plug, nipple adaptor, 600mm long uprising pvc pipe to reach H_O, 90^0 bend, 100mm long pvc pipe, 90^0 bend, 1000mm long pvc pipe to deliver digested biomass into digestate collection container. The threaded tee and plug were installed for ease of maintenance.
Gas outlet pipe (internal)	uPVC pipes and fittings	Size: 25mm diameter Length = 1550mm = H_E	**1**. Pipe size = 25mm	To maintain verticality, it is installed to stand on the floor of the digester with a tee with short-piece pipes end-capped

			2. Pipe Length = 1550mm **3.** Length of pipe from backnut = 500mm	cross-wise at the base. It is very important this component does not tilt to any side less the substrate enters and blocks it. The gas is conveyed out through another tee connected to a 25mm backnut.
Stirrer	Hand pump for substrate recirculation later changed to Aluminium profiles that can be seen in version 2 of the biogas plant	Length of reinforcing profiles = 1095mm = Gasholder diameter Length of paddles = 100mm each Number of paddles on each profile = 2 pcs.	Number of profiles installed = 2 pcs. Total Nr of paddles = 4 pcs.	The aluminium profiles were installed at 90^0 to one-another to reinforce the opened top of the gasholder with stainless steel self-tapping screws. Paddle-like profiles were screwed onto them designed to agitate the biomass with any rocking movement of the gasholder.
Gasholder guide pipe later changed to steel bracket + Circular steel belt and guide links as shown in version 2 of the biogas plant shown in Figure 4.2	Guide pipe in 40mm uPVC pipe connected to the gasholder with a backnut while the bracket was made with mild steel bar and links with mild steel square profiles	40mm uPVC pipe x 1.5m long Size of steel bar = 50mm wide x 3mm thick M16 × 150mm long bolt and nut. Link length = 520mm	Total Circular belt length = 3400mm Effective belt length = 3300mm Links = 2 Nr. x 520mm long total length including end guides.	The steel bar was made into a circular belt which is then worn round the gasholder and fastened at the ends with the bolt and nut. The circular bracket is linked to the two guide frame poles with rectangular profile links one end welded to a 50mm wide flat bar rolled circular to glide on the 50mm diameter guide frame poles and the other end configured into a trapezium to allow passage of the circular steel belt. The gasholder glide up and down the guide frame poles using this device.

	Bolt and Nut			
Gas pressurizing weight	Sandcrete blocks	Size = 225mm x 450mm x 225mm	Sandcrete blocks 225mm size Weight = 18kg Quantity = 2pcs	The Sand Crete blocks were used during biogas flaring and operation of the burners in the incinerator to stabilize the flame.
Gasholder guide frame	Galvanised iron pipes	Length = H_O digester + H_O gasholder + 200mm inside the ground and 300mm for biogas plant concrete base height = 1400 + 1311 +200 + 300 = 3211mm.	Total Length of poles =3211mm Height above ground level = 3011mm	The gasholder guide frame poles are carefully installed to be on a diagonal line passing through the centre of the digester tank for them to be able to centralize the gasholder tank in the digester tank for accurate readings.

3.2.5 Design of the incinerator system

The burner for the incinerator was designed using the equivalent heat obtainable from a 3kwh electric heater with a factor of safety of 25% and operational efficiency of 75% giving a required heat output of 5kwh or 18MJ.

3.2.5.1 *Design of the incinerator's auxiliary biogas burner and the biogas-air mixer*

In order to determine the size and the number of orifice/jets in the burner certain parameters must be determined. Applying Equation 2.31; the empirical form of the Bernoulli's theorem $Q = 0.0467C_dA_o\sqrt{\frac{P}{S}}$

Where P = Pressure of gas before orifice

Q= Gas flow rate

S = Specific gravity

C_d = Coefficient of discharge

A_o = Area of orifice

But $A_o = \pi d_o^2/4$ where d_o = diameter of orifice

Transforming Equation 2.31 to

$Q = 0.0467C_d \frac{\pi d_0^2}{4}\sqrt{\frac{P}{S}}$

And in conformity with Equation 2.41, $d_o = \sqrt{\frac{Q}{0.036C_d}}$ x $4\sqrt{\frac{S}{P}}$

These basic equations were then used to determine the following parameters:

1. Injector Coefficient of Discharge, (C_d):

This takes into consideration the vena contractor and friction losses through the orifice. For gas flow, the value lies between 0.85 – 0.95.

Here, C_d = 0.9 (assumed)

2. Specific gravity of biogas (S) = 0.94

3. Biogas flow pressure (P): Biogas is a low pressure gas. For this design the flow pressure was taken as

P = 10mbar = 102mm water gauge

4. Heat Output Required**:**

This was based on 3kwh. This is equivalent to 3 Nr. x 1kwh electric stove which produces three times enough heat for cooking.

Since the heat required in the small scale incinerator need to be just enough to kickstand the burning process since most of the materials to be incinerated are themselves fuel (sometimes referred to as Refuse Derived Fuel or RDF) with a lot of potential calorific energy.

Using a safety factor of 25% gives the value of 3.75kwh and @ 75% performance efficiency, this translates to

(100/75) x 3.75 = 5kwh

But 1kwh = 3.599×10^6J

Therefore, 5kwh = $5 \times 3.599 \times 10^6 = 18 \times 10^6$J

5. Biogas Flow Rate (Q)

Biogas specific energy = 20.8×10^6 g/m^3

Flow rate required Q = $(18 \times 10^6) / (20.8 \times 10^6) = 0.9$m^3/h

6. Stoichiometric Air Requirement

Applying Equation 2.26, $CH_4 + 2O_2 \rightarrow CO_2 + H_2O$

For this research, methane content of biogas produced is assumed as 60 % and air requirement for complete combustion taken as 1 volume of Biogas for 5.53 volume of air

7. Diameter of orifice, (d_o)

Applying Equation 2.41, $d_o = \sqrt{\frac{Q}{0.036 C_d}} \times 4\sqrt{\frac{S}{P}}$

With Q = 0.9m^3/h

P = 10mbar

S = 0.94 and

Cd = 0.9

$d_o = \sqrt{\frac{0.9}{0.036 \times 0.9}}$ x $4\sqrt{\frac{0.94}{10}}$

$d_0 = 5.27 \times 0.55 = 2.98$mm. The closest standard drill bit is 3mm diameter which will actually produce a hole slightly larger. Eventually, a hole of 4mm was used

8. Velocity of gas at the Orifice (*V*o)

Applying Equation 2.32, *V*o = $\frac{Q}{3.6 \times A_0 \times 10^{-2}}$

With Q in m^3/h and Ao in mm^2

$A_0 = \frac{\pi d_0^2}{4} = \frac{\pi \times 3^2}{4} = 2.25\pi$

$V_0 = \frac{0.9}{2.25\pi \times 3.6 \times 10^{-2}} = 3.6$m/s

9. Throat diameter, (d_t)

Where d_t is the diameter of the pipe conveying the biogas to the burner

Applying Equation 2.40, $d_t = \{\frac{r}{\sqrt{s}} + 1\}\ d_o$

d_o is the hole drilled for air to enter for the necessary Biogas-Air mixture ratio required for biogas to burn in air and r is the entrainment ratio.

2, 4 or 6 holes can be provided in pairs or 1, 2, or 3 holes can be provided in a single line of holes to serve this function to comply with the stoichiometric air requirement of 5.53.

Then $r = \frac{5.53}{\text{Number of holes}}$.

Using 1 hole and applying Equation 2.40, $d_t = \{\frac{5.53}{\sqrt{0.94}} + 1\}5 = 33.5$mm

This is higher than a standard 1 inch pipe (25mm) but also much higher than the 12.5mm ($^1/_2$ inch) pipe intended for use in this design.

Using 2 holes (1 pair) in Equation 2.40, $d_t = \{\frac{2.76}{\sqrt{0.94}} + 1\}5 = 19.27$mm (which is still higher than 12.5mm).

Using 4 holes (2 pairs) in Equation 2.40, $d_t = \{\frac{1.38}{\sqrt{0.94}} + 1\}5 = 12.13$mm (which is okay for a pipe of 12.5mm)

Therefore a minimum of 4 holes of 5mm diameter in 2 pairs drilled in a pipe of 12.5mm diameter will be sufficient to allow air to come in for the necessary Biogas-Air Mixture required for Biogas to burn in air.

10. Maximum possible aeration or entrainment ratio (r) at the biogas–air mixer:

Applying Equation 2.35 referred to as Prigg's formula

$r = \sqrt{S}\ \{\frac{d_t}{d_o} - 1\}$

With S = 0.94

$d_t = 12.5$mm

$d_o = 5$mm

$r = \sqrt{0.94}\ \{\frac{12.5}{5} - 1\} = 0.969\ (1.5) = 1.45$

If this is multiplied by the number of air inlet holes available

1 pair of holes i.e. 2 holes gives 2.9 which is not enough for a stoichiometric air requirement of 5.53

2 pair of holes i.e. 4 holes give 5.8 which is sufficient for a stoichiometric air requirement of 5.53. This implies that a $d_t = 12.5$mm is adequate for use with minimum 4 holes with diameter of 5mm for air inlet.

11. Gas pressure in the throat (P_t) of the burner,

Applying Equation 2.34, $P_t = P_o - \rho\ (V_o^2/2g)\ \{1 - (d_t/d_o)^4\}$

P_o = Atmospheric Pressure (1.013 bar)

ρ = density of gas (Biogas) = 1.0094kg/m^2

V_o = Velocity of gas in the Orifice = 3.6m/s

d_t = Throat diameter = 25.4mm

d_o = Orifice diameter = 3.5mm

$P_t = P_o - 1.0094 \times (3.6^2/2 \times 9.81) \{1-(3.5/25.4)^4\}$

$= P_o - 1.0094 \times (12.96/19.62)\{1-(0.14)^4\}$

P_t = (Po – 0.66) Pa = (10^5 – 0.66) Pa = 99.34 x 10^4Pa

12. Mixture Flow Rate at Optimum Aeration (Q_m)

Applying Equation 2.43

$$Q_m = \frac{Q\,(1 + r)}{3600}$$

But Q = 0.9m^3/h and r = 1.45

Therefore Q_m = 0.9(1 + 1.45) / 3600 = 0.0006125

= 6.125x$10^{-4}$$m^3$/s or 0.6 litres/sec.

This translates to a mixture flowrate of 2160 L/h.

At the stoichiometric Biogas: Air ratio of 1: 5.53, this works out at a biogas consumption of 331*l*/h well below the projected value of 600 *l*/h used to size the gasholder

13. Throat length or mixing length (L_t)

The throat length should be at least 10 times throat diameter according to Equation 2.39

$L_t = 10 \times d_t$

L_t = 10 x 12.5mm = 125mm

Biogas mixer length is 300mm in addition to the length of the 12.5mm G.I pipe used to connect the burner which is in excess of 950mm the radius of the Incinerator including the width of the red clay burnt brick used for the construction.

14. Reynolds number of flow through the throat, Re

The Reynolds number is required to calculate the pressure drop in the throat (Δp)

Applying Equation 2.37

$\text{Re} = \frac{\rho d_t V_t}{\mu}$

But from Equation 2.42

$V_t = \frac{Q_m}{A_t} = \frac{4Q_m}{\pi d_t^2}$ which gives

$\text{Re} = \frac{4\rho Q_m}{\pi \mu d_t^2}$

Using $Q_m = 6.125 \times 10^{-4} m^3/s$ and $d_t = 12.5mm$

And taking ρ for a mixture of Biogas and air as $1.15kg/m^3$ and $\mu = 1.71 \times 10^{-5}$ Pa

$\text{Re} = \frac{4 \times 1.15 \times 6.125 \times 10^{-4}}{\pi \times 1.71 \times 10^{-5} \times 0.0125^2}$

$= 335{,}658$

15. Pressure drop on the throat (Δp)

$\Delta p = \frac{f}{2} \rho V_t^2 (L_t/d_t)$

$\Delta p = \frac{f}{2} \rho \left(\frac{16 Q_m^2}{\pi^2 d_t^5}\right)$

For $Re > 2000$, $f = 0.316/Re^{1/4} = 0.316/ (335658)^{1/4}$

$= 0.013$

$\Delta p = \frac{0.013}{2} \times 1.15 \times [16 \times (6.125 \times 10^{-4})^2] / [\pi^2 \times (0.0254)^5]$

$= 0.43$ Pa

This pressure is much lower than the driving pressure in the throat

16. Total burner port area; A_p

Applying Equation 2.42 and 2.44

$A_p > Q_m/0.25$

$Q_m = 5.95 \times 10^{-4} m^3/s$

$A_p > (5.95 \times 10^{-4})/0.25 = 0.00238 m^2$

$A_p > 2.38 \times 10^{-3} m^2$

17. No of holes in burner port; n_p

Applying Equation 2.44

$n_p = 4A_p/\pi d_p^2$

$n_p = [4 \times 0.00238] / [\pi \times (0.0035)^2] = 337.5$ or 338 holes

Since there will be cross lighting, fewer holes shall be required. Say 300 holes or even less.

Previous work has shown that it is possible to reduce this number of holes by a quarter using flame stabilization when cross lighting of holes will occur. (Igboro, 2011)

For this research, 300 holes were drilled on three lengths of pipe.

- Orifice diameter of 3.5mm each was used in a pipe of 4mm thickness.
- The holes were spaced 4.5mm apart to allow for easy cross lighting
- Total Burner Port Area (A_p) is therefore

$$\frac{300\ [\pi(0.0035)^2]}{4} = 2.88 \times 10^{-3} m^2$$

Which is greater than the calculated A_p of $2.38 \times 10^{-3} m^2$ as required

- For Prigg's formula to hold, the value of $\frac{A_p}{A_T}$ must be between 1.5 and 2.2

$A_T = 3 \times \frac{\pi \times 0.025^2}{4} = 1.518 \times 10^{-3} m^2$

$\frac{A_p}{A_T} = \frac{2.88 \times 10^{-3}}{1.518 \times 10^{-3}} = 1.9$

3.2.6 Construction of the incinerator

The incinerator shown in Plate VII was constructed using as many local materials as possible according to dimensions and methods as described in Table 3.2

i. The combustion chamber was made from red clay burnt bricks.

ii. The chimney was made initially from red lateritic clay same as that used for the dome and later from 100mm mild steel pipe installed with an extractor fan to aid in sucking out the combustion gases.

iii. The incinerator dome was made from red lateritic clayey soil just like in a local bread oven.

iv. The auxiliary burner as shown in Plate XVI was made from 25mm diameter mild steel pipe and the mixing chamber from 80mm x 20mm mild steel rectangular pipe.

v. A biogas-air mixer as shown in Plate XVII was developed, fabricated and installed to ensure adequate mixture for combustion by the burner.

vi. Provision was made for secondary air injection to ensure complete combustion using an air blower and appropriately placed pipeworks for air delivery.

vii. The incinerator floor was made in steel grating with rods arranged to carry hollow burnt bricks for ash to drop into the ash recovery compartment below.

viii. A rain protective roof cover was installed for the incinerator dome using galvanised roofing sheet.

ix. The bottom ash recovery chamber was made in sandcrete blocks.

x. The gas produced by the biogas plant was piped underground to the incinerator system with reinforced polyethylene flexible hose in PVC conduit pipeworks.

Table 3.2: Incinerator Systems Components, Materials Specifications and Methods Description

Component	Materials	Dimensioning	Output Data	Methods, Implications and Remarks
Combustion chamber	Hollowed red clay burnt bricks.	Operational Volume = 66.7% Total Volume (i.e. Chamber Volume + Dome volume) $V_{dome} = (\pi/3)H^2(3R-H)$ Where H = height of dome and R = radius of dome $V_{dome} = (\pi/3)0.3^2(3x0.75– 0.3) = 0.35m^3$ Chamber Volume $\boldsymbol{V = \frac{\pi d^2}{4}H}$ Where d = diameter of chamber, H = height of chamber between the grating brick lining and base of dome $\mathbf{V} = (\pi \times 1.5^2 \times 1.5)/4 = 2.65m^3$	Chamber diameter = 1500mm Chamber depth = 1500mm Dome height = 300mm Dome Volume = $0.35m^3$ Total Volume = $2.65m^3 + 0.35 = 3m^3$ Operational Volume = $2m^3$	The combustion chamber was designed and constructed circular to maximize radiative heat currents. The heat reflects back equally from the walls towards the center thereby heating up the space faster than any other shape. Complete combustion is also aided in that there are no dead ends in the chamber.
Ash collection chamber	Sandcrete blocks	Chamber diameter = 1500mm Chamber height = 450mm	Chamber diameter = 1500mm	This chamber was constructed in standard 150mm Sand Crete blocks, two coaches high on top of a foundation of one coach buried in the

			Chamber height = 450mm	ground. The foundation blockwork was laid on 1:2:4 (cement : gravel : sand) concrete mix blinding. The floor was screed smooth to enable easy removal of combustion residue.
Incinerator dome	Red lateritic clay soil	Dome diameter = 1500mm Dome height = 300mm	Dome diameter = 1500mm Dome height = 300mm	It was necessary to continually fire the incinerator during construction to bake the red lateritic clay to hardness since construction was done in the rainy season.
Incinerator chimney	Mild steel pipe	Size = 100mm Height of chimney above installation level = 2000mm	Total height of chimney = 3950mm Total length of pipe = 2500mm	The chimney was fabricated in 100mm mild steel pipe installed to enter the combustion chamber just below the dome horizontally with a length of 500mm, then upright with a bend to a terminal height of 2000mm above the horizontal entry point. An extractor fan was installed to suck out the combustion gases
Waste loading & bottom ash removal	Mild steel angle iron Mild steel sheet Mild steel square pipe profiles	Size of angle iron: 32mm x 32mm Thickness of steel sheet: 2mm Size of square pipe: 25mm Door size: 600mm wide x 450mm high	Total length of 25mm square pipe = 4200mm (approx. 1 length)	The doors are made with 2mm thick mild steel sheets welded onto 25mm sized square mild steel pipe profiles. The door frames are made with 32mm x 32mm angle iron profiles

doors & frames		Height of waste loading door from the floor: 1500mm Height of waste loading door above the loading platform: 1200mm	Total length of 32mm angle iron = 4300mm (approx. 1 length) 75mm sized hinges = 4 pieces	The waste loading door opens by swinging towards the waste loading platform for safety of the operator against blow-out.
Air vent for primary air and burner lighting ports	Space between red clay bricks	Size of primary air vent: 50mm x 150mm Size of burner lighting ports: 75mm x 150mm	The ports 50mm x 150mm are evenly distributed round the incinerator's entire circumference. Two ports are 75mm x 150mm for lighting the burners	Allowance for air entrance into the combustion chamber was made by leaving a space of 50mm in-between one block and the next when laying the first coach of burnt clay bricks. Primary air enters the chamber through these ports, two of which were enlarged as burner lighting ports.
Grating brackets	Mild steel rod	Size: 12mm Dimension: 200mm x 150mm x 200mm U-shaped	No. of brackets installed = 6 pieces equidistant round the incinerator at 425mm from the floor of the ash compartment.	The waste grating holding brackets are made with 12mm mild steel rods bent in a U-shape. The long ends are crossed with 50mm bits of iron rod welded on and embedded on top of the blockwork used in making the ash compartment

Waste grating (lower and upper)	Mild steel rods Steel hinges Mild steel wire mesh	Lower grating Size of steel rods: 12mm Size of hinges: 100mm Upper grating Steel wire mesh semi-circular in two halves of 500mm radius	Two lengths of 12mm rod each 12m long + 3 No. hinges (100mm size) Steel wire mesh semi-circular in two halves of 500mm radius	The lower waste grating is made from mild steel rods bent in a circular frame of 1500mm diameter with bars arranged to hold the hollow blocks that will line the grating. In addition it is constructed in two halves of semicircle with hinges that opens and closes in one plane, to enable folding and ease of installation and removal for maintenance activities. The Upper waste grating is a semi-circular steel wire mesh in two halves of 500mm radius
Grating brick lining	Hollow red clay burnt bricks	Quantity: 6 pcs	Total No. of bricks used to line the grating = 6 pcs	The bricks were used to line the lower grating and holding the upper grating which prevent the waste from laying directly on the burners
Auxiliary Gas burner	Mild steel pipe Mild steel rectangular profile	Size of pipe: 25mm Lengths of burners: 360mm, 500mm, 360mm Size of mixing chamber: 32mm x 75mm rectangular profile x 1000mm long Orifice: 3mm Supply sockets: 12.5mm x 2No.	Three lines of burners of lengths: 500mm, 360mm and 360mm. Total No. of burner ports = 300 holes	The auxiliary gas burners and holders are made from mild steel pipe 25mm diameter. The burners are drilled with 3mm sized holes at an angle of 45^0 and 315^0 to the vertical. The burner ports are 3mm diameter and 5mm from the next hole in line for effective cross-lighting. The biogas burner is as shown in Figure 4.6

Air blower for secondary air	Electric powered air blower	Air Blower Specifications: Input Power: 600W Rated voltage: 220 – 240V Frequency: 50 – 60 Hz Wind Pressure: 8000Pa Wind Volume: 2.8m^3/min Rated Speed: 13000rpm Model: Raider Professional Tools Electric Blower RDBL2570	Quantity: 1nr	An air blower is installed for supply of secondary air for complete combustion. Once combustion has commenced successfully in the chamber the air blower keeps the burning progressing by injecting additional air
Air injection pipes	Mild steel pipes and fittings	Size: 12.5mm		An air injection pipe gantry made in 12mm galvanised iron pipes is installed to deliver the air from the air blower into the waste in the combustion chamber
Rain protection roof	Mild steel Roofing sheet Wood Mild steel pipes	As required		The roof was constructed on four poles 3m high in wood and zinc coated steel roofing sheets to protect the incinerator dome from rainfall.

Biogas-air mixing device	Galvanised iron pipe, sockets, brass nipples, copper pipe	As per design		This is specifically designed and fabricated for use in mixing air and incoming biogas before it reaches the burner. It is shown in Figure 4.7
Flue gas extractor fan	Mild steel	Size: 100mm		This is an adaptation of the extractor fan used on septic tanks for use to suck out the flue gases from the combustion chamber

3.2.7 Operation and testing of the biogas plant

In most processes when methane is designed to be produced from municipal solid wastes by Anaerobic Digestion (AD) three basic steps are involved. The first step involves preparation of the organic fraction of the solid wastes for AD. This includes: Receiving, Sorting, Separation and Size reduction. The second step involves the addition of moisture and nutrients, blending, pH adjustment, temperature adjustment and anaerobic digestion in a reactor, with facility for content mixing and holding the biomass for a period of time usually measured in days. The third step involves capture, storage, and if necessary, separation of the gas components evolved during the digestion process.

In this study, the biogas was generated from the organic portion of the municipal solid waste after grinding as shown in Plate IX. It was blended in a 2:1 ratio with abattoir waste to bridge the decay lag phase. The mix was then poured into the digester for fermentation.

Daily readings of temperature, pH and level of gasholder above the digester were taken. Record of the readings are shown in Appendix 3. Weekly samples of digested biomass was taken and analysed for Nitrate, phosphate, potassium, sulphate and total organic carbon content at the ABU Institute for Agricultural Research (IAR), Samaru, Zaria and the results are shown in Appendix 4.

The biogas was flamed after two weeks using a Bunsen burner as shown in Plate XVIII and later with a biogas stove fabricated at Ahmadu Bello University in a previous study as shown in Plate XIX. It was piped to the incinerator with a reinforced polyethylene flexible hose installed in a PVC conduit pipework and connected through the biogas – air mixer to the incinerator's auxiliary burner. Plate XX shows the auxiliary burner in operation in the incinerator, the bottom ash was collected as shown in Plate X for

analysis. The result of the analysis as well as that of a mixture of the ash with the digestate from the Biogas Plant are shown in Appendix 4

An experiment was conducted in the Laboratory to determine the energy content / calorific value of the gas produced by the biogas plant and the data was analysed and result obtained. The set-up for the Laboratory experiment was as shown in Plate VI.



Plate IX: Grinding the solid waste to increase the surface area for degradation



Plate X: Sample collection of the incinerator's bottom ash

3.2.8 Operation and performance of the incinerator

In an incinerator the burner is required to start the burn cycle. After the waste is ignited, it is kept burning by the injection of air. The burner is shut down once the combustion chamber operating temperature is achieved. This takes about 15 to 30 minutes in a small scale incinerator with auxiliary air blower. The burner might be required again for some time during the burn cycle if the temperature of the combustion chamber falls below expected levels usually indicated by the type of plume coming out of the chimney or readings on an installed temperature measuring device.

Three trial burning of 100 litres of waste per trial was carried out to evaluate the incinerator system performance.

Finally, the ash, one of the by-products of the incinerator system was analysed for nutrient content. It was also mixed with the digestate, one of the by-products of the biogas plant and analysed for nutrient content.

3.2.9 Determining the energy content or calorific value of the biogas as a fuel

The calorific value of the biogas was determined by using a measured amount of the fuel to raise the temperature of a known quantity of water and calculating the heat absorbed by the water. Table 3.3 shows the data sheet for the laboratory trials carried out and the laboratory set up was as shown in Plate VI in the section listing the materials for laboratory work

Table 3.3: Data obtained in experiment to determine the energy content of the biogas

Data specification	Trial 1	Trial 2	Trial 3
Mass of beaker + water (g)	200.5	197.9	201.3
Mass of empty beaker (g)	101.8	97.7	101.5
Mass of water, m_w (g)	98.7	100.2	99.8
Specific Heat Capacity of Water C_p (J/g^{0}C)	4.18	4.18	4.18
Final Water Temp (^{0}C)	44	45	44
Initial Water Temp (^{0}C)	24	24	24
Change in Temp Δt (^{0}C)	20	21	20
Initial mass of biogas + tube and accessories	1075.2	600.8	750.5
Final mass of biogas + tube and accessories	1074.7	600.2	750.0
Mass of biogas fuel burned, m_f (g)	0.5	0.6	0.5
Heat energy liberated, $H = \Delta t \times m_w \times C_p$ (J)	8251.32	8795.56	8343.28
Energy Content of the fuel (J/g)	16,502.64	14659.26	16686.56

3.2.10 Performance evaluation of the incinerator

Table 3.4 present the data recorded while operating the incinerator in an attempt to evaluate its performance.

Table 3.4: Performance measurements of the incinerator system

Parameters	Trial Nr 1	Trial Nr 2	Trial Nr 3	Mean
Quantity of materials introduced (L)	100	100	100	100
How many times burner was re-ignited	3	2	4	3
Cumulative period burner was in operation (mins)	20	15	25	20
Total biogas consumption (L)	136	110	180	142
Operating temperature achieved after 30 minutes of combustion (^{0}C)	920	960	905	928
Quantity of materials left after 1hr of combustion (L)	23	17	20	20
Quantity of bottom ash produced after 1hr of combustion (L)	4	5	4.5	4.5

CHAPTER FOUR

RESULTS AND DISCUSSION

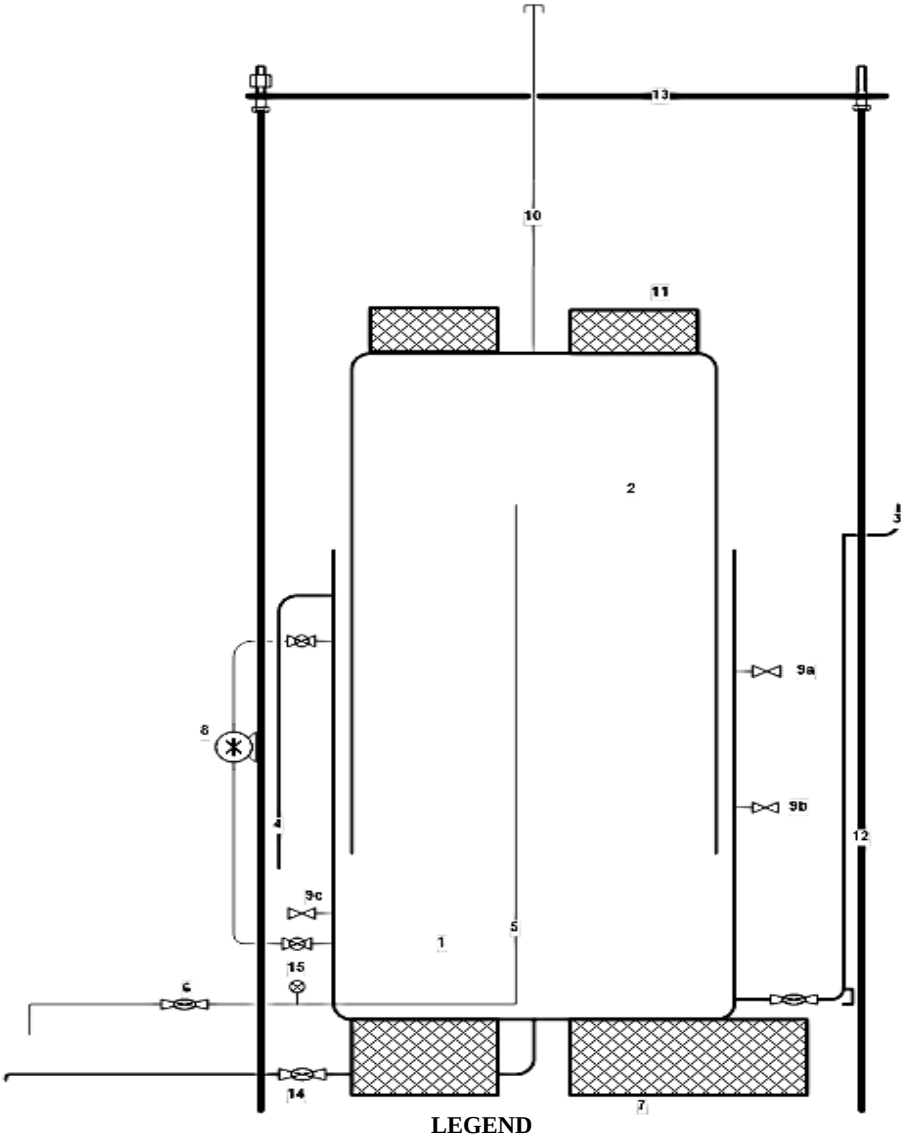
Various concepts of the chosen theme for the design and construction of the combined biogas plant and incinerator system were tried out. It was discovered that some concepts did not work well in actual operation. These were redesigned and replaced with more workable concepts and the resultant biogas plant and incinerator system were operated and data obtained were analysed with conclusions and recommendations reached.

4.1. Biogas Plant version 1

Figure 4.1 and Plate XI shows the first version of the installed biogas plant. There was a challenge in mixing the substrate due to settling of the particulates. The hand pump (item 8 on Figure 4.1) installed to recycle the substrate with a view to effecting the necessary mixing of the biomass; which is a major operational design consideration, was continually getting blocked by the substrate particulates. The challenge was overcome with the installation of static mixers made from aluminium profiles as shown by item 8 in Figure 4.2. Mixing of the biomass was effected by movement of the gasholder 10^0 clockwise and anticlockwise a few times about the central pipe guide twice daily while taking temperature and pH readings.

The other challenge encountered was that of gasholder leakage. The choice of using standard plastic water tank available in the market for the digester and gasholder comes with the inherent challenge of the need to seal the standard factory provided inlet and outlet apertures on the tank. The sealing has to be constantly checked for leakage by the application of soapy water to produce bubbles if there is any leakage. The experience in this study was leakage in the first five weeks which coupled with the settling of biomass on the uncut portion of the top of the inverted tank used as gasholder shown in Plate XII, did not allow any appreciable rise in the gasholder for measurement

of the volume of gas produced. It is therefore recommended that preparation of the gasholder tank should involve complete removal of the whole top of the tank leaving only the cylindrical portion.



LEGEND

1. – Digester
2. – Gasholder
3. – Feedstock inlet
4. - Digestate outlet
5. – Gas outlet pipe (internal)
6. – Gas release valve and pipe (external)
7. – Digester concrete stand
8. – Hand pump
9. – Sampling points
10. – Gasholder stabilizer
11. – Gas pressure weight
12. - Stabilizer stand
13. – Stabilizer cross bar
14. – Sludge release valve and pipe
15. – Pipe clips

Figure 4.1: Biogas Plant version 1



Plate XI: Biogas Plant version 1

4.2 Biogas Plant version 2

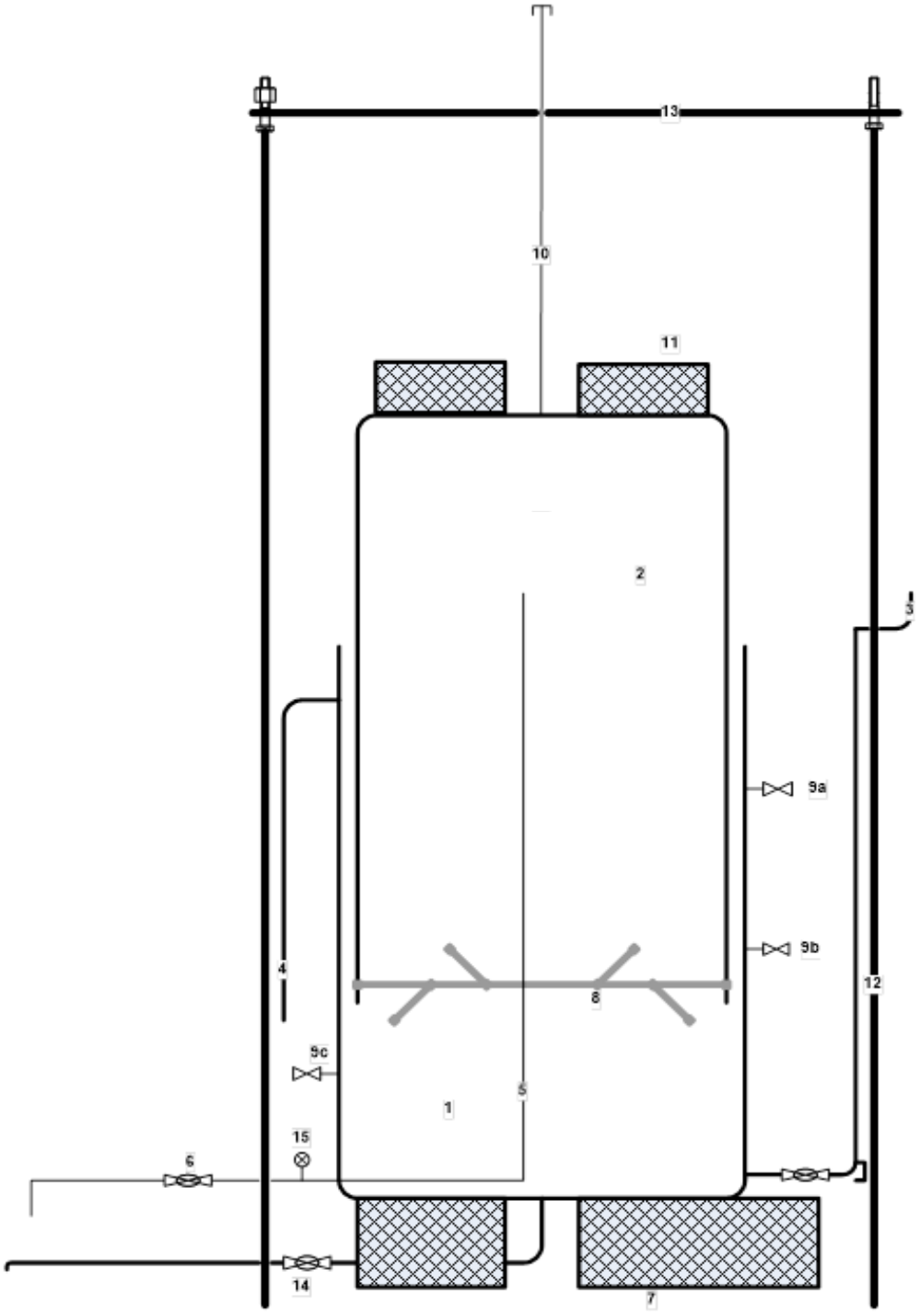
In order to resolve the mixing and gasholder sealing challenges, the gas produced was stored in gas cylinders and tyre tubes using a refrigerator compressor as shown in Plate XIII, and the rest flared off by burning. The gasholder was removed for repairs and amendment. The second version of the biogas plant was installed as shown in Figure 4.2. The digester was charged with additional substrate and daily readings of temperature, pH and gasholder level continued. The system was so efficient that within a few days gas production pushed the gasholder to its limiting height of the cross bar. The wooden cross bar failed under pressure from the gas in the gasholder and was replaced with a cross bar made out of galvanised iron pipe.



Plate XII: Gasholder tank showing uncut portion of the top



Plate XIII: Storing of the biogas in tyre tubes



LEGEND

1. – Digester (2000 Ltr tank)
2. – Gasholder (1500 Ltr tank)
3. – Feedstock inlet
4. - Digestate outlet
5. – Gas outlet pipe (internal)
6. – Gas release valve and pipe (external)
7. – Digester concrete stand
8. – Stirrer
9. – Sampling points
10. – Gasholder stabilizer
11. – Gas pressure weight
12. - Stabilizer stand
13. – Stabilizer cross bar
14. – Sludge release valve and pipe
15. – Pressure gauge

Figure 4.2: Biogas Plant version 2

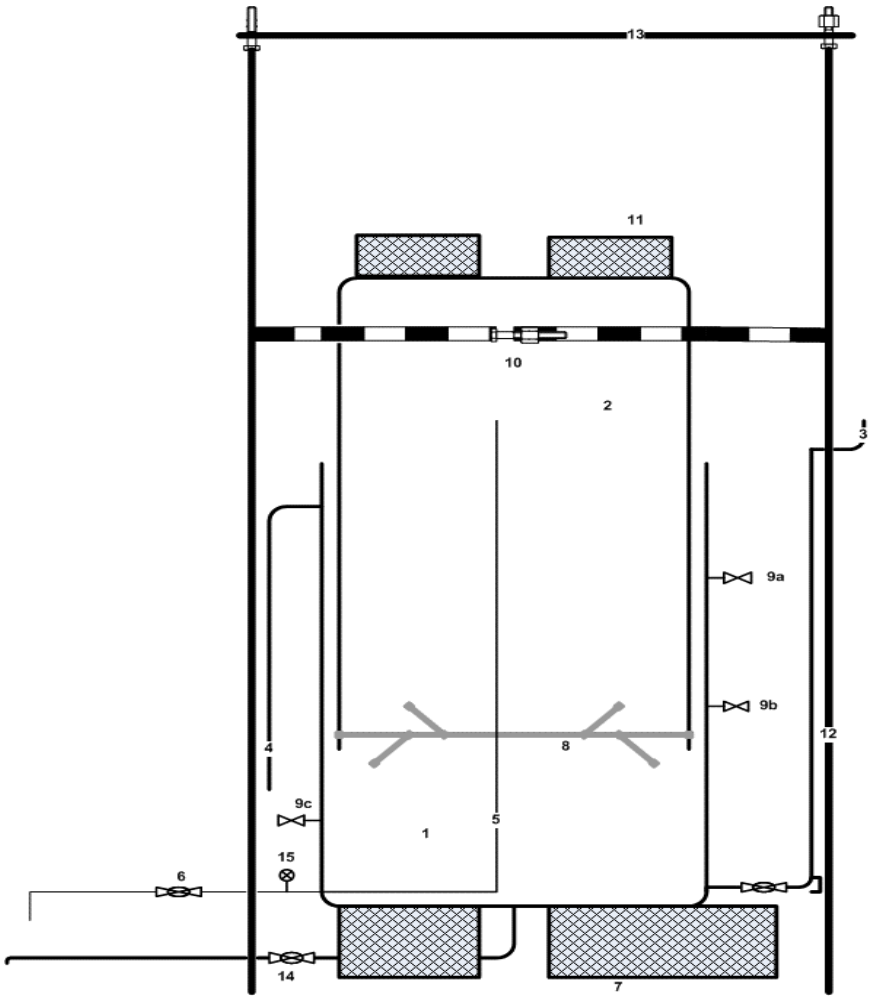


Plate XIV: Reinstallation of the gasholder after installing the static mixer

4.3 Biogas plant version 3

It was a challenge to keep the gasholder PVC pipe guide centralised in the hole in the gasholder limiting cross bar as a result of wind load and possibly uneven substrate density distribution within the digester. This resulted in failure of the wooden cross bar guiding the gasholder vertical guide pipe. This resulted in a redesign of the gasholder guiding system. A circular metal belt and links was devised to hold the gasholder and guide its rise above the biomass sliding up and down the two guide poles as biogas is produced and utilised respectively. The failure of the PVC guide pipe would have resulted in biogas leakage if the gas had been tapped out of this component as is usual

in floating gasholder designs. The biogas tapping with pipeworks out of the stationary digester cylindrical tank however resolved this potential problem. Substrate mixing in this final version of the Biogas Plant was effected by moving the gasholder about the links on the guide frame poles as fulcrum to create a rocking movement that enables the installed static mixers to stir the content of the digester.



LEGEND FOR BIOGAS PLANT

1. – Digester tank (2000 *ltr*)
2. – Gasholder tank (1500 *ltr*)
3. – Biomass feed pipe
4. – Digestate outlet pipe
5. – Gas outlet pipe (Internal)
6. – Gas release valve (external)
7. – Digester tank concrete stand
8. Stirrer
9. Sampling Taps
10. Gasholder bracket
11. Gas pressurizing weight
12. Gasholder guide frame
13. Guide frame cross bar
14. Slurry decanting valve
15. Pressure gauge

Figure 4.3: Biogas Plant version 3

4.4. Incinerator system version 1

The incinerator chimney as well as the dome was constructed of red lateritic clay. It was plastered over with cement and sand as protection from rainfall as shown in Figure 4.4 and Plate XV. It was observed that rain water enters the cracks that developed in the plastering of the dome weakening it and eventually resulting in failure of the dome structure.

The first version of the incinerator was operated with the biogas stove shown in Plate XIX developed by Igboro, (2011) at the WREE department, ABU, Zaria

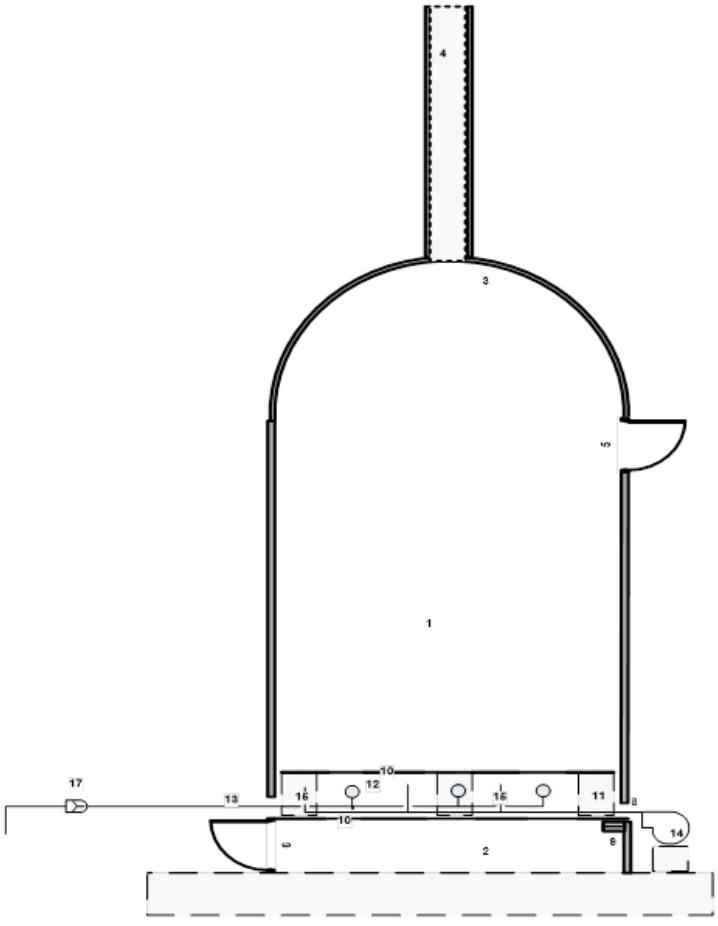


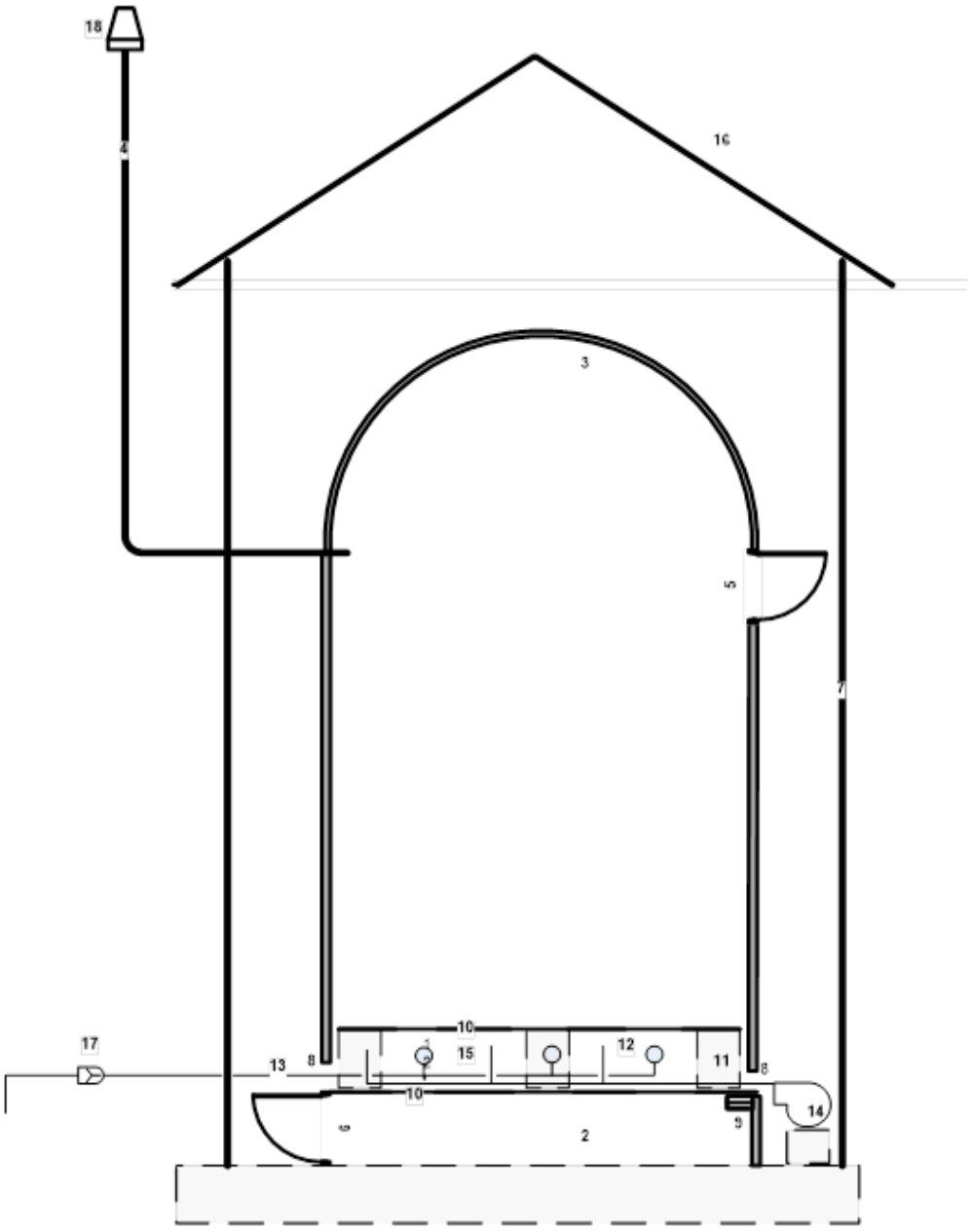
Figure 4.4: Incinerator system version 1



Plate XV: Incinerator system version 1

4.5 Incinerator system version 2

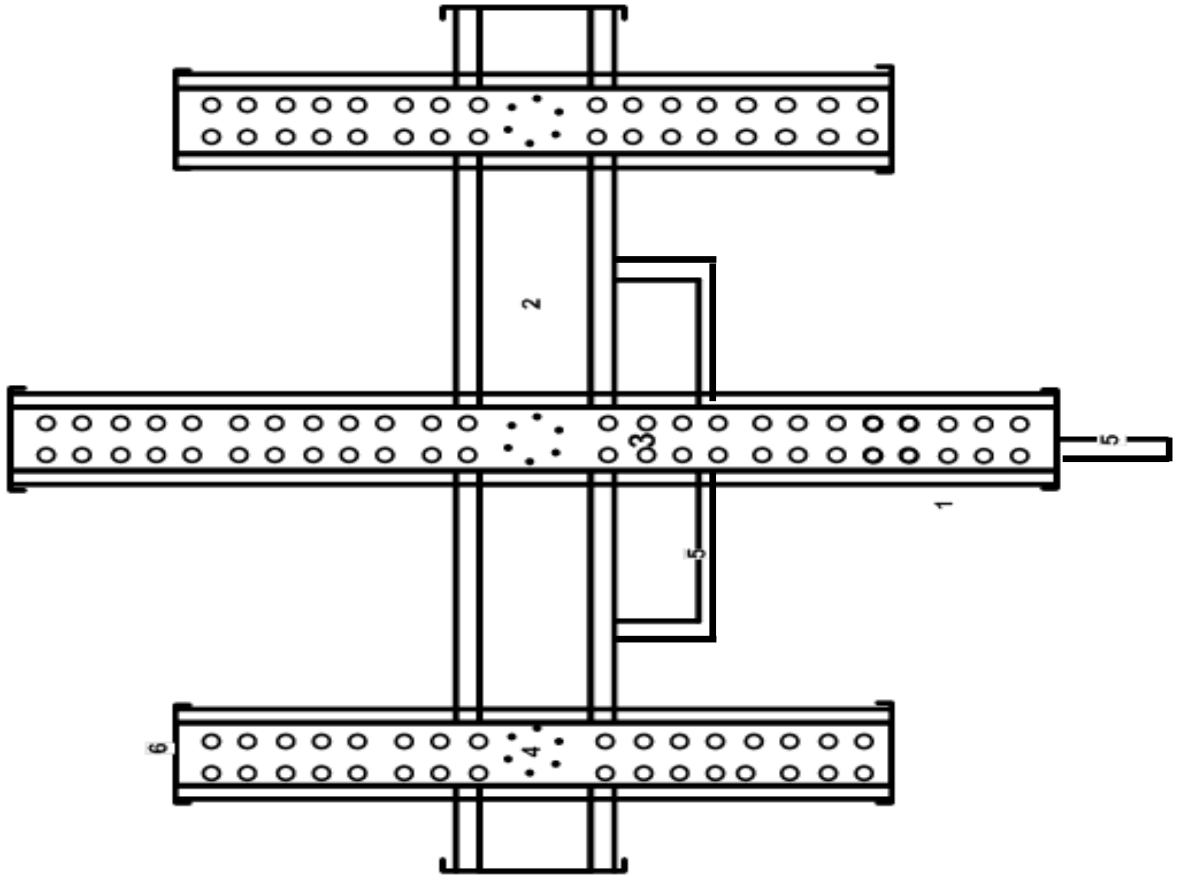
The exhaust system for this version was redesigned using mild steel pipe to exit the incinerator just below the base of the dome horizontally then vertically upwards. (Item 4 in Figure 4.4). An extractor fan was installed to aid removal of the flue gases. (Item 18 in Figure 4.4). The rain protection roofing (item 16 in Figure 4.4) was installed to protect the incinerator dome from rainfall as shown in Plate VII. An auxiliary burner was designed and fabricated and installed as well as a biogas-air mixer for combustion efficiency.



LEGEND

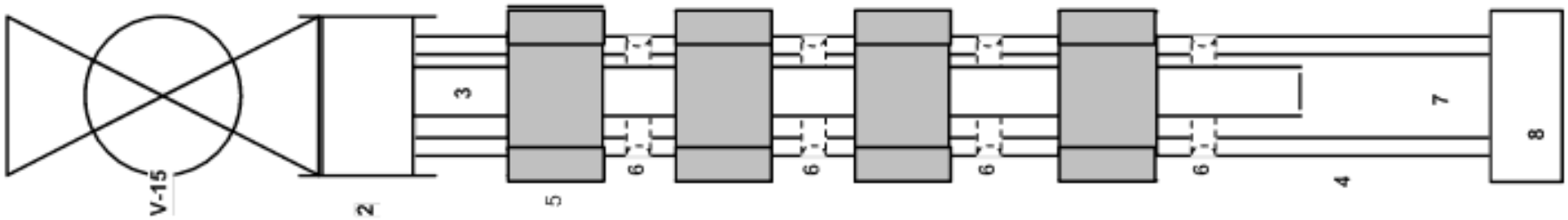
1. Combustion chamber
2. Ash collection chamber
3. Incinerator dome
4. Incinerator chimney
5. Waste loading door
6. Bottom ash removal door
7. Rain protection roof stand
8. Air vent for primary air
9. Grating brackets
10. Waste grating
11. Grating brick lining
12. Gas burners
13. Gas burners holder
14. Blower for secondary air
15. Air injection pipes
16. Rain protection roof
17. Biogas-air mixing device
18. Flue gas extractor fan

Figure 4.5: Incinerator system version 2



Legend		
BIOGAS BURNER		
Symbol	Count	Description
1.		Gas burner pipe port
2.		Mixing port
3.		Burner holes
4.		Burner/mixing port link
5.		Mixing Tube/pipe from Biogas-Air mixer
6.		End caps

Figure 4.6 Plan view of the Biogas burner



Legend		
BIOGAS – AIR MIXER		
Symbol	Count	Description
1.		Gas Inlet ball valve
2.		Threaded bushing
3.		Gas inlet pipe
4.		Theaded G.I. Pipe as mixer body
5.		Threaded Socket
6.		Air entrainment holes
7.		Mixing tube
8.		Union Connector

Figure 4.7: Biogas – Air Mixer for the auxiliary burner



Plate XVI: The incinerator's auxiliary burner



Plate XVII: The biogas –air mixer for the incinerator's auxiliary burner



Plate XVIII: Flaming biogas with a Bunsen burner



Plate XIX: Biogas flaring using ABU biogas stove



Plate XX: The incinerator's auxiliary biogas burner in operation

4.6 Biogas Production

Figure 4.8 shows the daily gas production during the period of digestion period while Figure 4.9 shows the equivalent graph of the cumulative gas production during the same period.

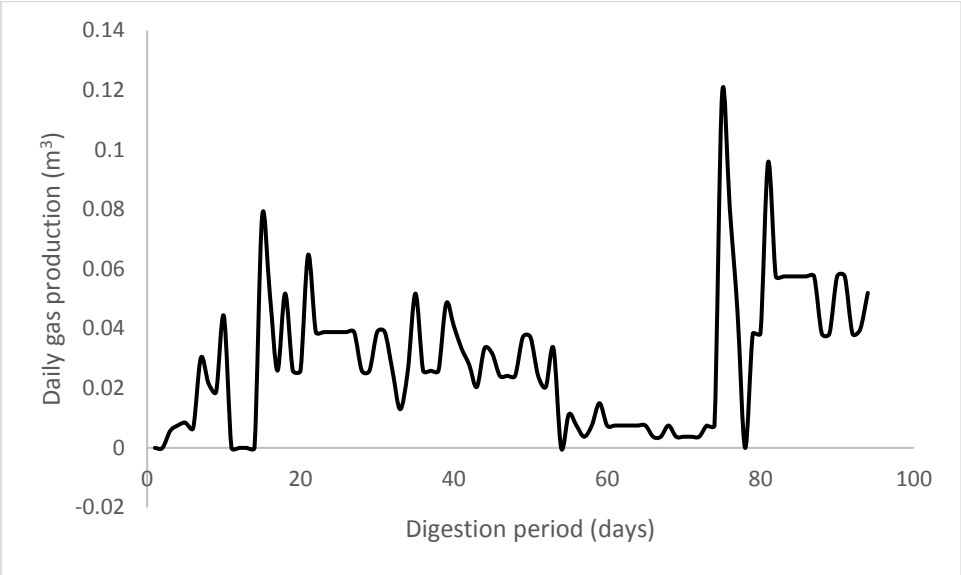


Figure 4.8: Daily gas production during digestion period

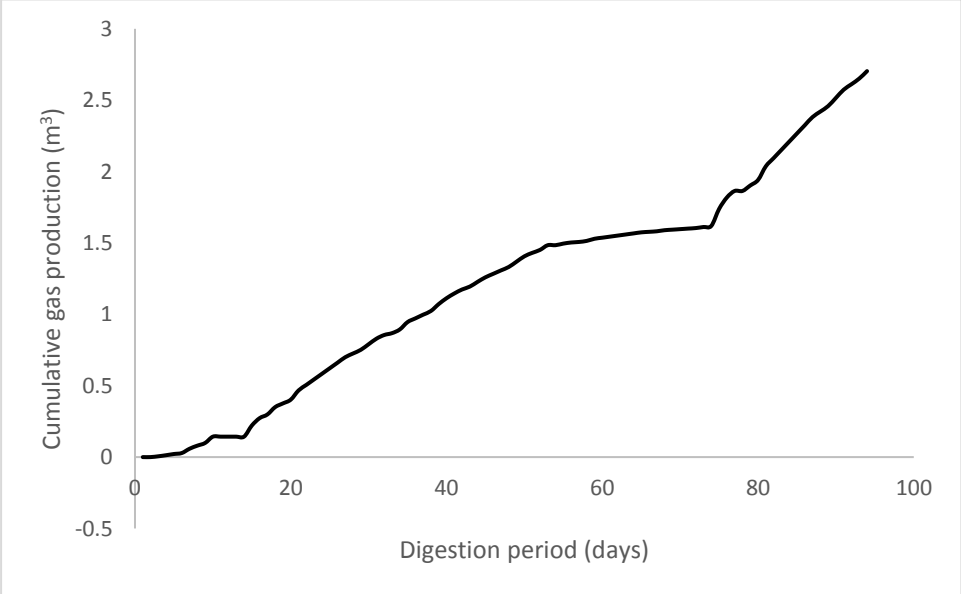


Figure 4.9: Cumulative gas production during digestion period

The efficacy of the digester in producing biogas is in three phases. Lowest between day 3 – 11; 0.143m^3 (0.018m^3/kg), highest between day 15 – 55; 1.353m^3 (0.034m^3/kg) and medium between day 55 – 94; 1.208m^3 (0.031m^3/kg)

4.7 Digester and Samaru Temperatures during Digestion Period

Figure 4.10 shows the ambient temperature of Samaru, Zaria where the Biogas Plant was located in comparison to the temperature of the digester during the digestion period. It can be seen that the digester temperature is always lower than the ambient temperature and was within the mesophilic range of 20 – 40 ^{0}C throughout the whole period. This shows that it is feasible to install a biogas plant using similar materials in a similar environment without installing any form of temperature control accessories like lagging to maintain temperature during the night or roofing as sun shade to reduce heat from the sun during the day.

The maximum temperature recorded was 40.5^{0}C while the minimum was 24^{0}C

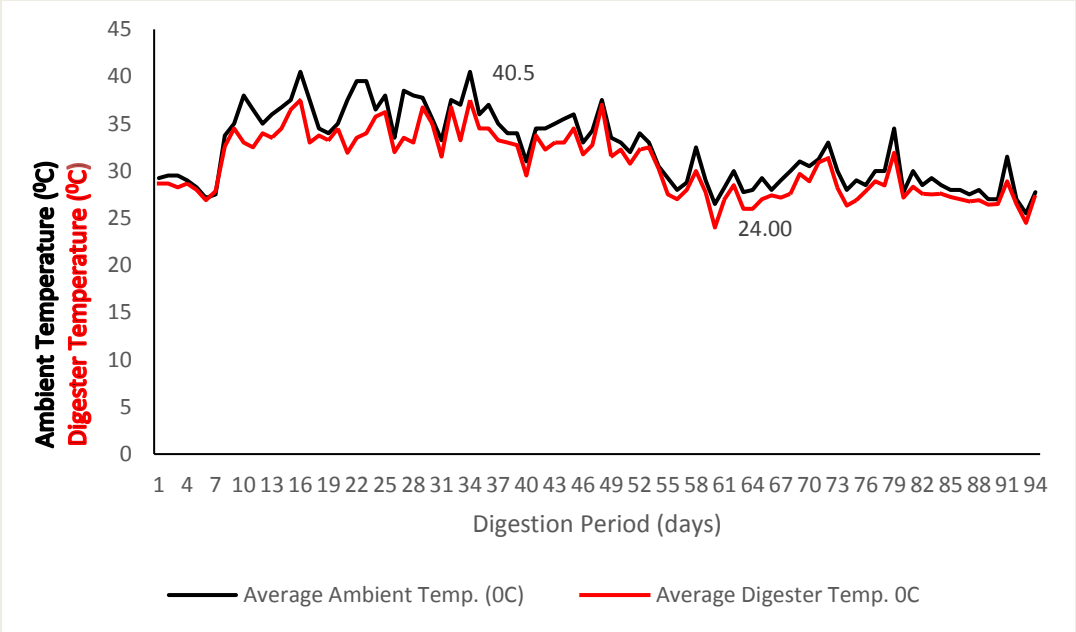


Figure 4.10: Average ambient and digester temperature during digestion period

4.8 Digester pH during biogas production

Figure 4.11 shows the digester pH during the period of digestion. The pH line follow the theoretical prediction of pH in a healthy digester. A slight drop in pH during hydrolysis, a sharp drop in pH during the acid forming stage of acidogenesis, a rise in pH during acetogenesis and pH tending towards neutral during the gas production phase of methanogenesis. In conformity to expectations according to observations in previous studies (Igboro, (2011); Alfa, (2013)), gas production ceases for a short period of time when the pH fell below the value of 3.5 as shown in Figure 4.12 when the plot of pH and gas production during the digestion period was compared.

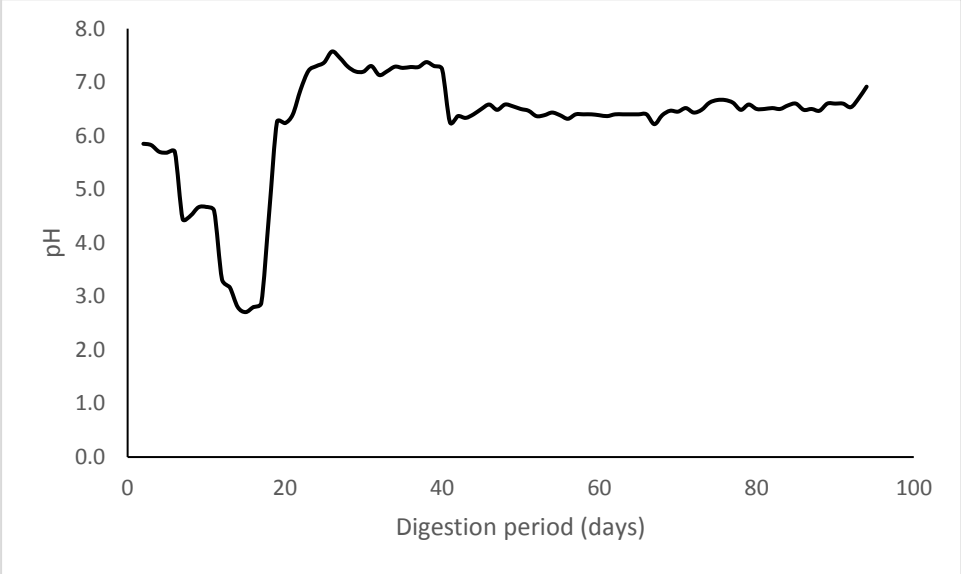


Figure 4.11: Average digester pH during digestion period

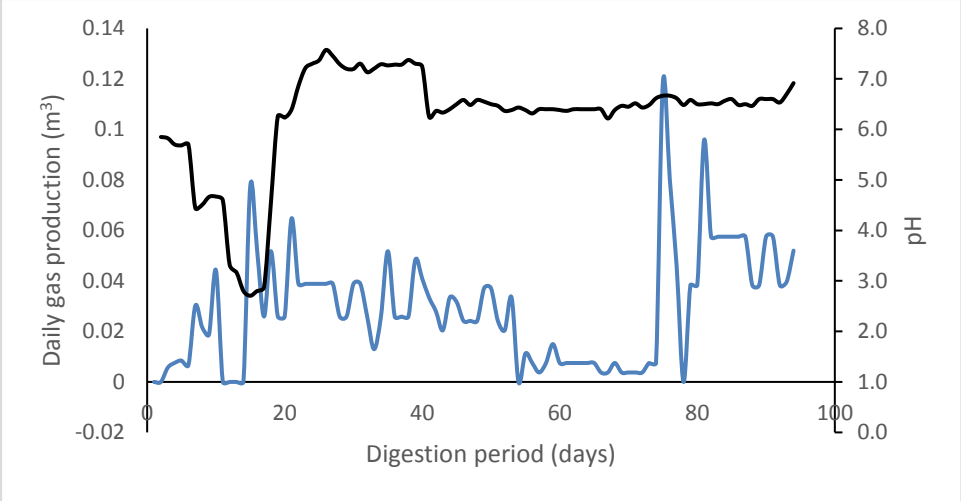


Figure 4.12: Gas production in relation to pH during digestion period

4.9 Result of analysis of the digested substrate

4.9.1 The pH level of the digestate at different time intervals

Figure 4.13 shows the result of the analysis of the digestate at different time intervals during the digestion period. The result shows a virtually neutral pH level at a mean value of 7.27 indicating non-toxicity. It could therefore be readily applied to the soil as a conditioner and crops for plant nutrient uptake according to Hartmann *et al*., (2002) and Whiting *et al*., (2010).

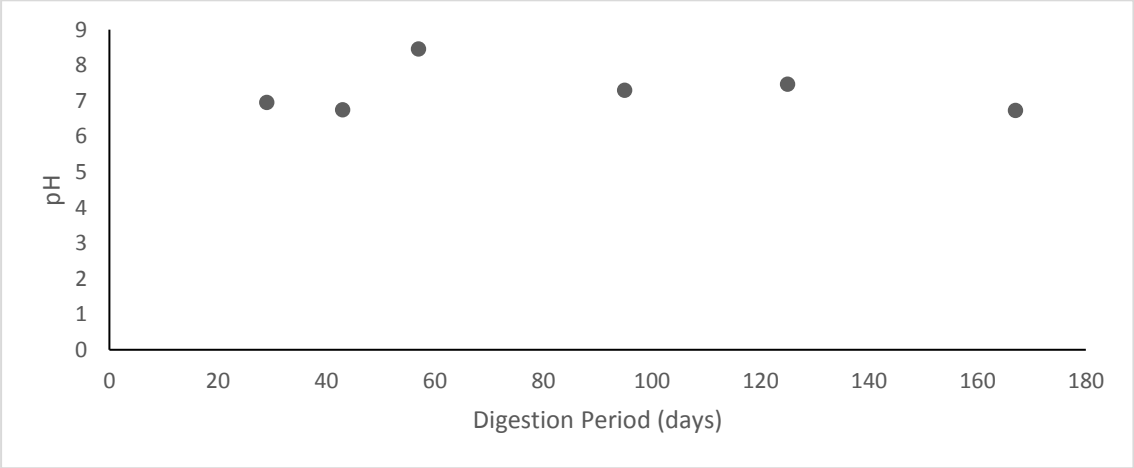


Figure 4.13: The pH of the digestate at different time intervals

4.9.2 The total potassium content of the digestate at different time intervals

Figure 4.14 shows the result of the analysis of the dgestate at various times intervals for the total potassium content. According to the linear trend line the potassium content of the digestate over time is virtually constant at an average of about 400mg/l.

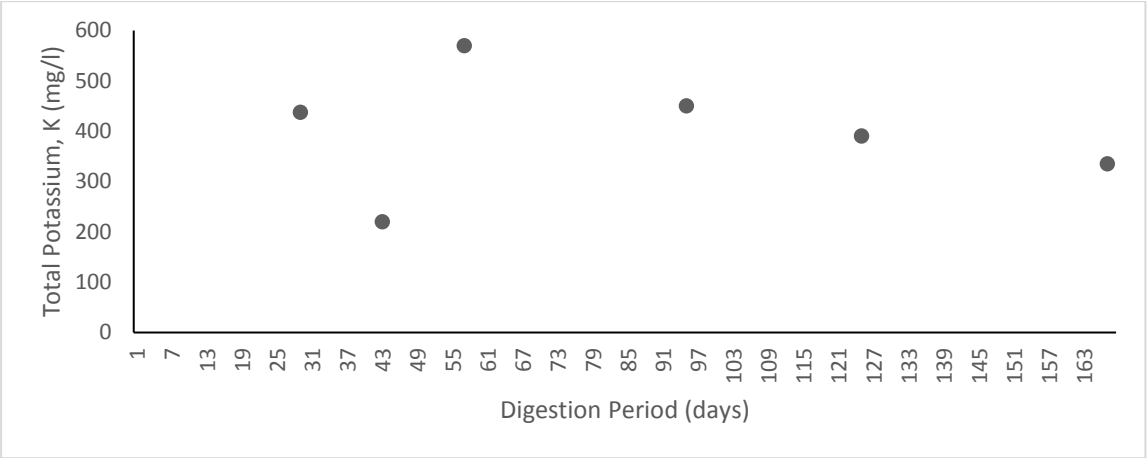


Figure 4.14: Total potassium content of the digestate at different time interval

4.9.3 Total Phosphate content of the digestate at different time intervals

Figure 4.15 shows the result of the analysis of the digestate for total phosphate content. The result indicates a steadily increasing level the longer the time is from the first loading date of the digester. This is in conformity to a previous study at ABU. (Igboro, 2011). However the content is much higher than that in the previous study. While Igboro, (2011) had a total phosphate content in the range of 0.4 – 0.8mg/l, the present study had values in the range of 60 – 110mg/l with a mean of 89mg/l

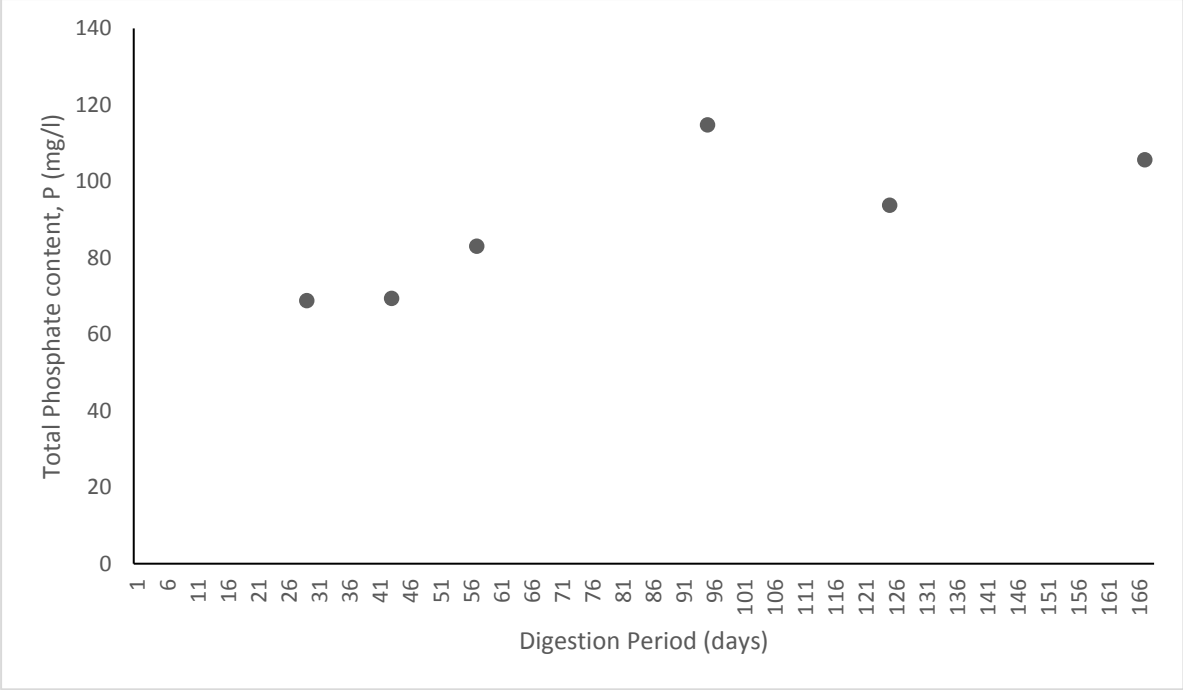


Figure 4.15: The Total Phosphate content of the digestate at different time intervals

4.9.4 Nitrate content of the digestate at different times intervals

Figure 4.16 shows the result of the analysis of the digestate at different time intervals for nitrate levels. The result shows declining levels with time in conformity with previous findings (Igboro, 2011). The mean value is about 2.8%

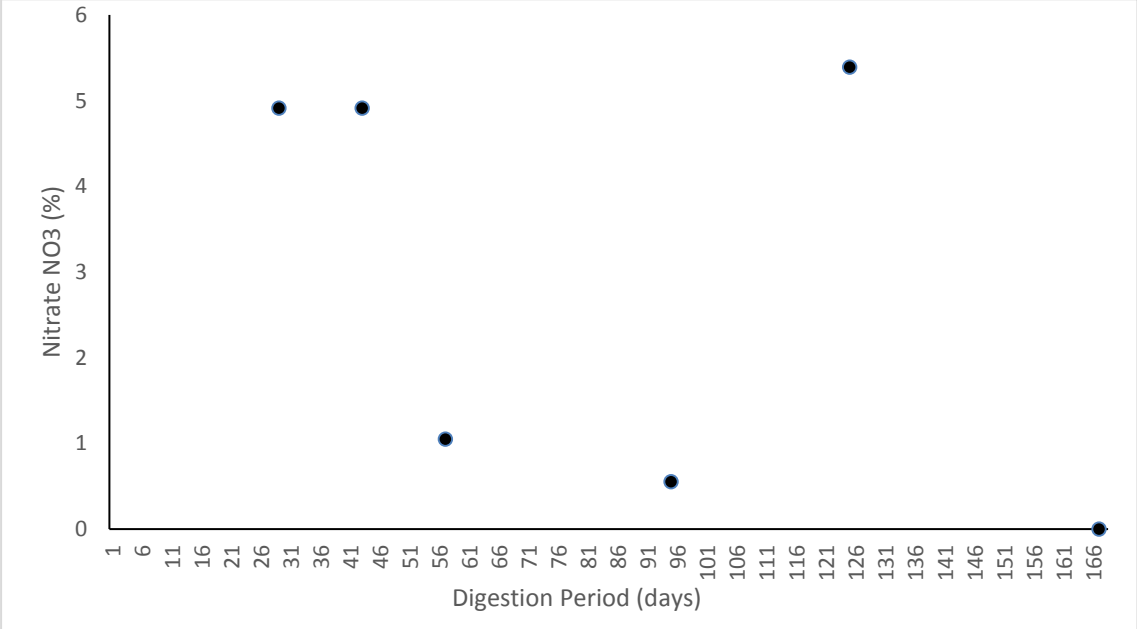


Figure 4.16: The Nitrate content of the digestate at different time intervals

4.9.5 The total Sulphate content of the digestate at different time intervals

Figure 4.17 shows that the total sulphate content of the digestate declined with time. The sulphate content of the digestate was relatively high for the first two samples at slightly over 300mg/l before reducing to an average of about 50mg/l for the remaining four samples taken.

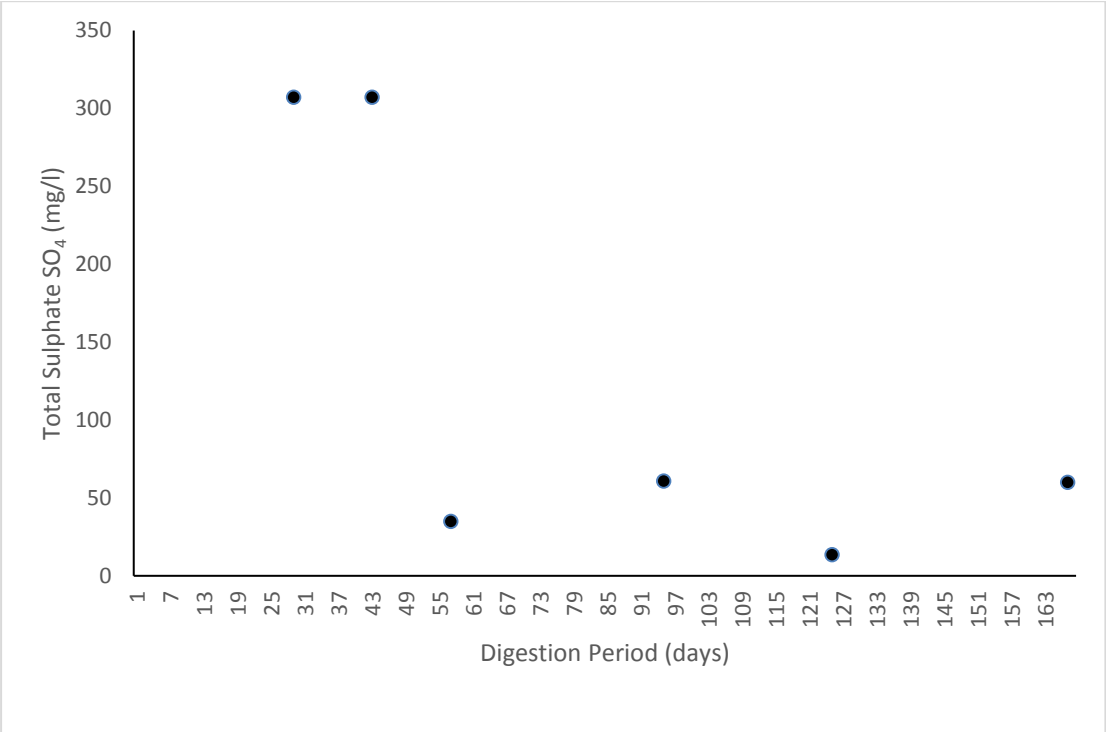


Figure 4.17: The total sulphate content of the digestate at different time intervals

4.9.6 Total Organic Carbon (TOC) content of the digestate at different time intervals

Figure 4.18 shows a declining TOC level with time which is indicative of the efficiency of the process since the organic carbon is the energy source. The average is about 0.16%

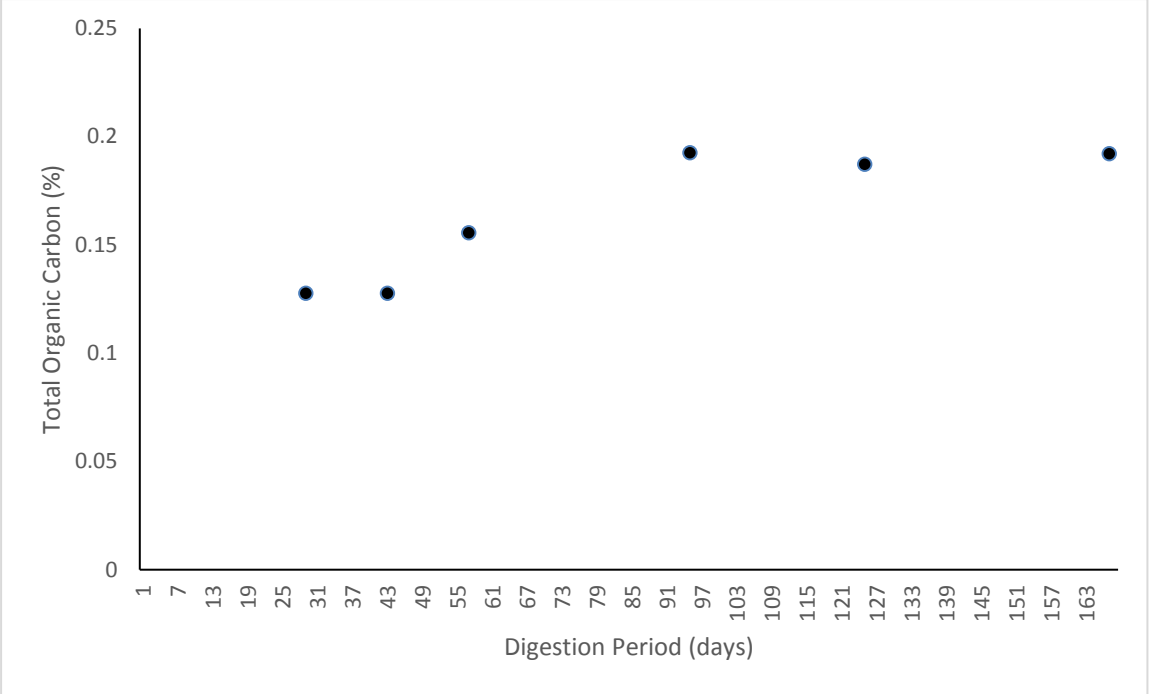


Figure 4.18: Total organic carbon content of the digestate at different time intervals

4.10 Performance evaluation of the incinerator

From the data recorded while operating the incinerator, performance evaluation of the system was carried out and shown in Table 4.1

Table 4.1: Performance evaluation of the incinerator system

Parameters	Trial Nr. 1	Trial Nr. 2	Trial Nr. 3	Average
Biogas consumption (L/min)	6.8	7.3	7.2	7.1
Quantity of materials burnt within the period (L)	77	83	80	80
Quantity of bottom ash produced after 1hr of combustion (L)	4	5	4.5	4.5
Percentage reduction of waste in the incinerator	77 %	83 %	80 %	80 %

The operating temperature of the incinerator determined during this preliminary trial tests would need to be confirmed with more rigorous testing. There was also the

challenge of one of the line of burner flaming out due to wind speed but the incinerator operation was not affected once the waste has caught fire and is burning. The high draught was controlled by the installation of primary air vent shutters. Eventually, the high wind speed turned out to be more of a plus than a challenge to the incinerator's operation making it unnecessary to operate the blower most of the time.

4.11 Evaluation of the analysis of the mixture of the combined systems' by-product

The by-product of the combined treatment systems; digestate from the biogas plant and ash from the incinerator were analysed separately and mixed. The result of the analysis is shown in Figure 4.19 and 4.20.

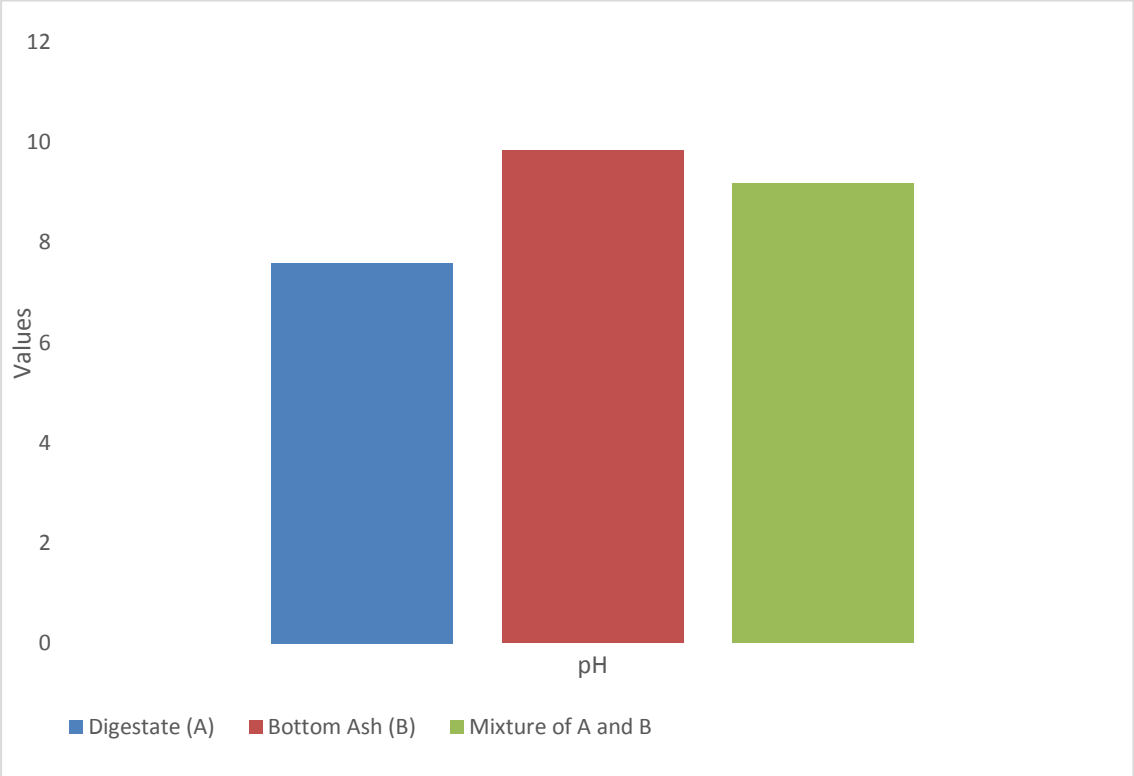


Figure 4.19: Comparing the pH values of the by-products separately and combined

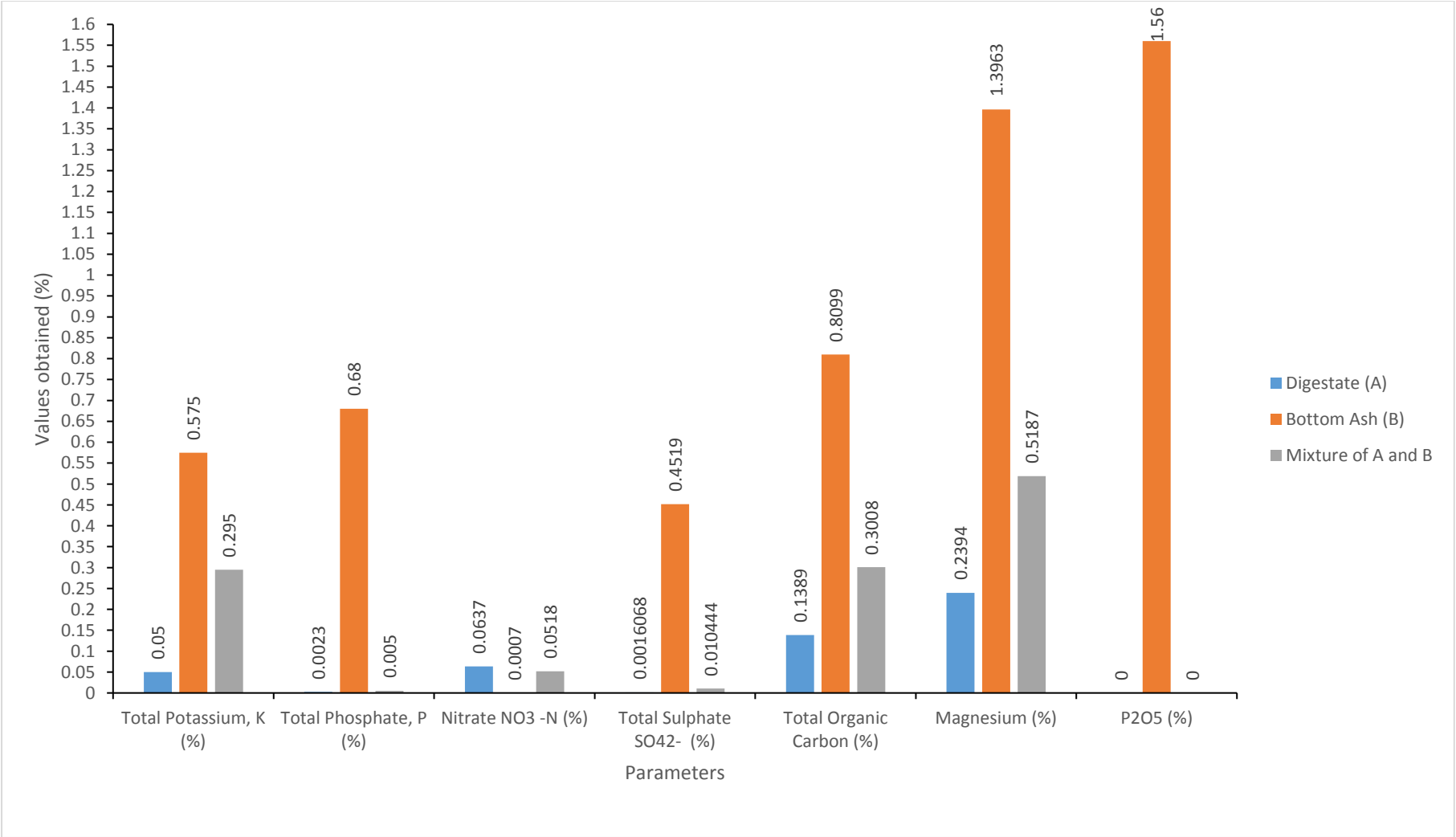


Figure 4.20: Comparing the nutrient contents of the by-products separately and combined

The ash has higher nutrient contents of all the parameters analysed except for nitrate. But these nutrients have been highly mineralised and would most likely leach away if applied directly to the soil as fertilizer. However, a mixture with the digestate, an organic fertilizer may bind these nutrients and release them slowly to crops making the mixture a better organic fertilizer than the digestate alone. This is an issue worthy of recommendation for further research.

4.12 Calorific value of the biogas as a fuel

From the data obtained in the experiment to determine the energy content of the biogas produced as shown in Table 3.3. The Average Calorific value of the biogas as a fuel is calculated to be 15,949.49 J/g

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In general conclusion, the aim and objectives of the dissertation was achieved in that a prototype biogas plant was designed and constructed. Innovative piping was introduced to convey the gas out of the stationary digester making it safer from gas leakage than is hitherto practiced from the moving gasholder. Stand-alone support and innovative steel belt and guide links were introduced for the moving dome gasholder and aluminum profile was used as an innovative static mixer in the moving gasholder for optimal performance of the digester.

A small scale municipal solids waste incinerator was built with locally available burnt lateritic bricks for the body and grater linings and clay for the dome. Good flame stability for a small scale incinerator was achieved with an innovative biogas air mixer which was developed to aid complete combustion of the biogas while using the also newly developed incinerator auxiliary biogas burner.

Finally, the digestate from the biogas plant showed nutrient content in conformity to previous studies for similar product concluded to have improved crop yield at ABU. In addition analysis of the mixture of the digestate and the ash from the incinerator shows the possibility of having discovered a better organic fertilizer in the combined systems' by-product.

Specific and measurable conclusions are:

1. This study resulted in the construction of a biogas plant to produce biogas from municipal solid waste (MSW). It incorporates a shredder for the MSW and blending with abattoir waste, the biogas plant produces between day 3 – 11; 0.143m3 (0.018m3/kg), highest between day 15 – 55; 1.353m3 (0.034m3/kg) and medium between day 55 – 94; 1.208m3 (0.031m3/kg).

2. It also builds a small scale village/community (approximately 50 houses) sized incinerator using locally available materials with the capacity to burn 1.8m^3 of solid waste per day burn cycle while utilizing the biogas as kick-off fuel. It thus has the ability to reduce the volume of the remaining combustible waste by approximately 94% by volume.
3. Digestate from the biogas plant has fertilizer value. Average values obtained for nutrient content are Nitrate 2.8%, Phosphate 89mg/l, Potasium 400mg/l, Sulphate 130mg/l, TOC 0.1638% with the pH at 7.2.
4. The biogas produce a blue flame of about 870^{0}C without scrubbing with an experimental calorific value of 16,000J/g or 16MJ/kg.
5. An auxiliary biogas burner was developed for the incinerator and it has a biogas consumption rate of 7.1L/min or 426 litres/hr using a designed and developed biogas-air mixer installed to complement the burner's operation.
6. Analysis of the nutrient composition of the mixture of the digestate from the biogas plant and the bottom ash from the incinerator compared to their separate baseline values indicated higher pH, Total Organic Carbon, Magnesium, Potassium, Phosphate and Sulphate with only the Nitrate content of the ash lower, possibly making the mixture possibly a better organic fertilizer than the digestate alone.
7. The amount of solid wastes at abattoirs in Nigeria which are presently a nuisance can be used to produce biogas for income generation from the proceeds of the sale or use of the fuel.

5.2 Recommendations

1. It is necessary to bring the output of this study to the attention of policy makers so that pilot schemes can be tested in real life situations in our urban centres as a mix in our solid waste management strategies.

2. Biogas production facilities should as a matter of National policy be integrated in the design and construction of new abattoirs in Nigeria.
3. It is recommended that further studies be encouraged to investigate possible improvement in soil condition and crop yield from application of the mixture of the digestate and bottom ash
4. It is also necessary to investigate the efficiency of the developed biogas burner and biogas-air mixer as one of the main challenges in the operation of the small scale incinerator was flame stability of the auxiliary burner.

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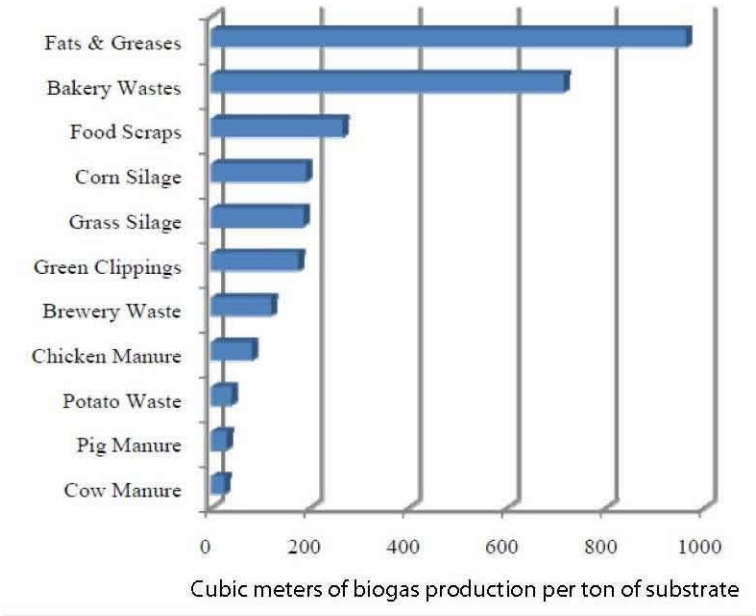
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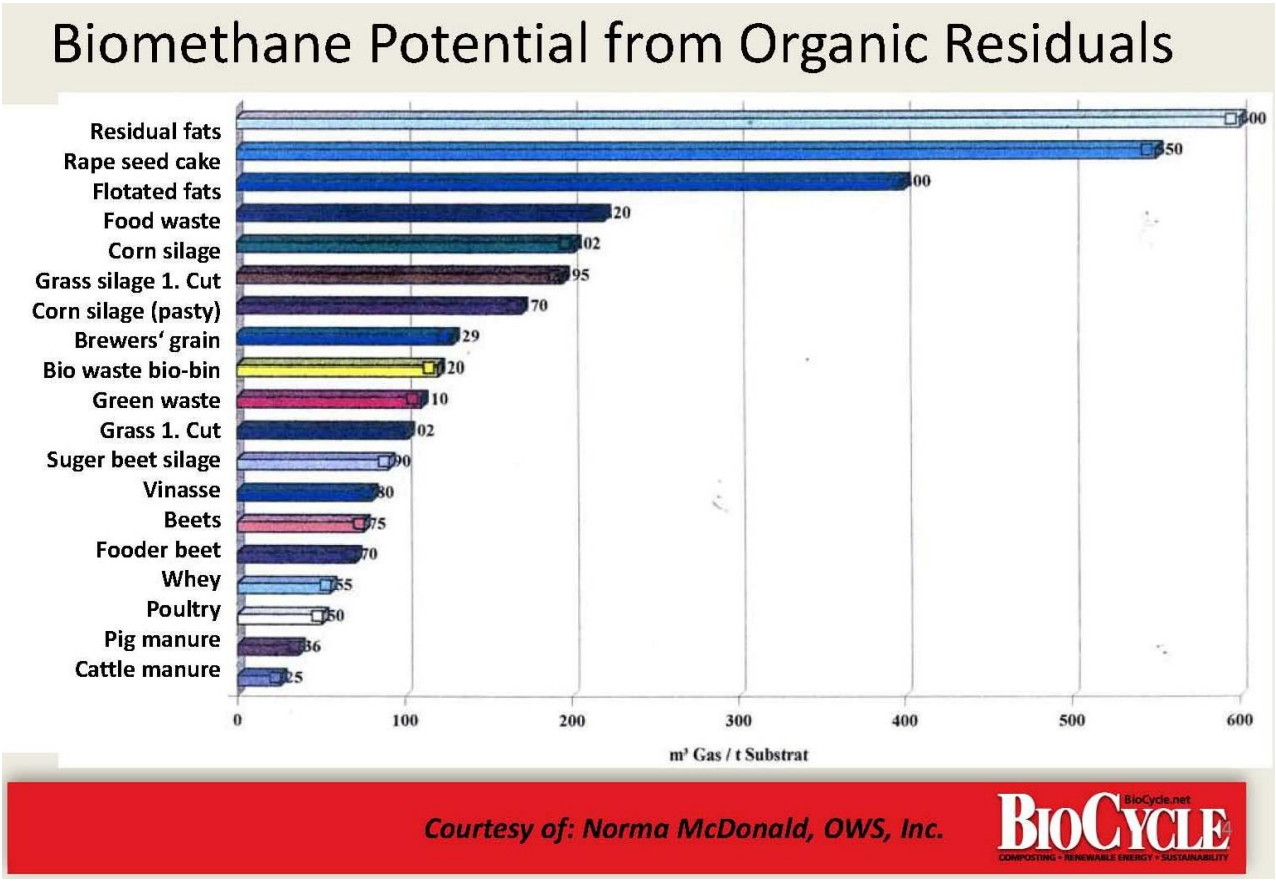
APPENDICES

Appendix 1

Biogas production potential of various substrates



Appendix 2



Appendix 3

Result of Analysis of Digested Effluent from the Biogas Plant at ABU, Zaria

Parameter/ Date of sampling	25/4/16	28/4/16	05/03/16	25/6/16	25/7/16	05/09/16	Mean
Period after Loading (days)	30	44	58	96	126	168	87.00
pH	6.95	6.74	8.45	7.29	7.46	6.73	7.27
Total Potasium, K (mg/l)	437.5	220	570	450	390	335	400.42
Total Phosphate, P (mg/l)	68.75	69.32	82.96	114.77	93.73	105.6	89.19
Nitrate NO_3 N (%)	4.914	4.914	1.05	0.553	5.39	0.0014	2.80
Total Sulphate SO_4 (mg/l)	307.07	307.07	34.96	60.85	13.51	60	130.58
Total Organic Carbon TOC (%)	0.1277	0.1277	0.1556	0.1926	0.1873	0.1921	0.16

Appendix 4

Result of the analysis of the combined treatment systems by-products

Sample	Digestate (A)	Bottom Ash (B)	Mixture of A and B
pH	7.59	9.84	9.18
Total Potassium, K (%)	0.05	0.575	0.295
Total Phosphate, P (%)	0.0023	0.68	0.005
Nitrate NO_3^{-N} (%)	0.0637	0.0007	0.0518
Nitrate NO_3^{-N} (mg/l)	637.00	7.00	518.00
Total Sulphate SO_4^{2-} (mg/l)	16.068	-	104.44
Total sulphate SO_4^{2-} (%)	-	0.4519	-
Total Organic Carbon (%)	0.1389	0.8099	0.3008
Magnesium (%)	0.2394	1.3963	0.5187
P_2O_5 (%)	-	1.56	-

Appendix 5

BILL OF QUANTITIES FOR A BIOGAS PLANT AND INCINERATION CENTER

S/N	DESCRIPTION OF ITEM	QTY	UNIT	RATE	AMOUNT
1	Plastic Tank 2000 litre	1	Nr	28,000	28,000
2	Plastic Tank 1500 litre	1	Nr	22,000	22,000
3	Elbow 2”	7	Nr	500	3,500
4	Back nut 2”	5	Nr	2,000	10,000
5	Plug 2”	2	Nr	500	1,000
6	Pipe uPVC 2”	3	length	1,200	3,600
7	Back nut 1"	2	Nr	1,000	2,000
8	1” x 1/2” reducing bush	1	Nr	250	250
9	1/2" pvc pipe	4	length	400	1,600
10	1/2" ball valve	2	Nr	350	700
11	2" ball valve	1	Nr	2,000	2,000
12	1/2" flexible hose	10	m	150	1,500
13	Clips for 1/2” hose	4	Nr	200	800
14	4”x 2” wood including drilling	1	length	2,500	2,500
15	Circular Steel belt bracket for gasholder	1	Nr	9,000	9,000
16	Concrete stand for digester	1	Lot	20,000	20,000
17	Pressure gauge + fittings	1	Lot	4,500	4,500
18	Weighing scale	1	Nr	5,000	5,000
19	Kitchen scale	1	Nr	6,000	6,000
20	Thermometer	1	Nr	5,000	5,000
21	pH meter	1	Nr	12,000	12,000
22	Calibration metre tape on gas holder	1	Lot	500	500
23	Sampling taps	3	Nr	1,000	3,000
24	1” Tigre uPVC Pipe	2	length	1,100	2,200
25	1” elbow	2	Nr	100	200
26	Hand pump for mixing	1	Nr	8,000	8,000
27	2" G.I Pipe for Gas holder guide frame	2	Nr	3,500	7,000
28	3/4" uPVC pipes for water supply to site	14	length	550	7,700
29	Fittings for water supply to site	1	Lot	15,700	15,700
30	Welding and Plumbing labour	1	Lot	15,000	15,000
31	Transportation of materials to site	1	Lot	20,000	20,000
32	Fencing and Gate	1	Lot	30,000	30,000
33	Cable, conduit and gear switch for electrical connection including workmanship	1	lot	65,000	65,000
34	Fabrication of Waste Grinder	1	Lot	300,000	300,000
35	Miscellaneous expenses including transportation and handling of waste grinder	1	Lot	89,150	89,150
	SUB-TOTAL FOR DIGESTER, WASTE GRINDER, WATER & POWER SUPPLY TO SITE				**704,400**

	INCINERATOR				
1	6" sandcrete blocks	34	Nr	150	5,100
2	6" red bricks	145	Nr	200	29,000
3	cement	4	bags	1,600	6,400
4	sand	10	barrows	300	3,000
5	Ash chamber door	1	Nr	1,500	1,500
6	Iron rod + bending for support bracket	1	Lot	1,900	1,900
7	Mason workmanship	1	Lot	10,000	10,000
8	Dome construction	1	Lot	20,000	20,000
9	Waste Inlet door	1	Lot	2,000	2,000
10	Exhaust Pipe + bracket + stand	1	lot	10,000	10,000
11	Emission gases scrubbing device	1	Nr		0
12	Supply and Install Air blower	1	Nr	8,500	8,500
13	Air inlet pipeworks	1	set	4,000	4,000
14	Gas inlet pipeworks and Nozzle carrier	1	set	4,000	4,000
15	Incinerator waste carrying Grater	1	Nr	6,500	6,500
16	Incinerator auxilliary burners	1	Lot	11,000	11,000
17	Gas piping from Biogas plant to Incinerator	1	Lot	21,000	21,000
18	Incinerator Roof + Roofing Poles	1	Lot	25,000	25,000
19	Refractory bricks grating lining	30	Nr	200	6,000
20	Miscellaneous expenses including plastering dome with cement and sand and firing to harden	1	Lot	21,290	21,290
	SUB-TOTAL FOR INCINERATOR				**196,190**
	TOTAL BIOGAS AND INCINERATOR SYSTEM				**900,590**
	MISCELLANEOUS ITEMS				
1	PPE (Personnel Protective Equipment)	1	Lot	11,000	11,000
2	Fire Extingusher	1	Nr	5,000	5,000
3	"No Naked Flame" Signboards	1	set	4,000	4,000
	SUB-TOTAL FOR MISCELLANEOUS ITEMS				**20,000**
	GRAND TOTAL FOR PROJECT				**920,590**