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PROMOTION OF THE PRODUCTION AND USE OF RENEWABLE ENERGY IN AN URBAN AREA; CASE STUDY SMALL SCALE BIOGAS PRODUCTION FROM FAECAL WASTE, YAOUNDE

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Engineering (MEng) in Environmental Engineering

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DEDICATION

This work is dedicated to God Almighty and to my beloved family, who stood by me throughout these years of studies and was a source of inspiration, endlessly providing me with spiritual, financial and moral support.

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ABSTRACT

Due to the increase in population followed by its demand for energy, increasing amount of faecal waste or sludge with its improper management, there is a need to cut across these factors with the notion of renewable energy through anaerobic digestion. Anaerobic digestion (AD) is a technology which exploits the ability of anaerobic bacteria consortia to solubilize, degrade and produce large amounts of biogas from a wide variety of organic matter. In a controlled environment, AD ensures a proper disposal of organic matter leading to a reduction of greenhouse gas emissions and foul odors that may affect the surrounding population. The main objective of this work was to 'to encourage the making and use of renewable energy through small scale production of biogas in an urban area like Yaoundé for a sustainable living'. This work was carried out through the aid of questionnaires, interviews, laboratory analysis and past studies on faecal sludge management (FSM). This work covered the environmental, economic and energy aspects related to the management of FS in a home or institution of at least six (6) people. The study showed that an estimate of 72.35 kg of waste is produced daily in this home or institution. This waste has the capacity of producing 1151.11 litres of methane daily equivalent to 0.58 kg of Liquefied Petroleum Gas (LPG) which is more than the average amount of cooking gas used daily by this home or institution. Sizing of the various components of the biogas system was based on the fact that the anaerobic digester will use a semi-solid feed, operate on a semi-continuous mode and employ the use of thermophilic bacteria with the possibility of recycling the digestate in a fixed dome digester. The estimate of the investment into the project was determined at 600,000 FCFA including an annual cost of operation and maintenance. The investment has a profitability index of 1.13 within a period of 15 years showing that is a value added project. The structure will need a period of 6.5 years to regain the initial investment into the system. Based on the assessment, anaerobic digestion is a feasible and viable treatment technology for FSM.

Keywords: Anaerobic digestion, biogas, faecal sludge, renewable energy, Yaoundé

RESUMÉ

Du au fait de l'augmentation de la population suivie de sa demande en énergie, de l'augmentation de la quantité des déchets fécaux ou des boues avec sa mauvaise gestion, il est nécessaire de recouper ces facteurs avec la notion d'énergie renouvelable par digestion anaérobique (DA). La DA est une technologie qui exploite la capacité des consortiums de bactéries anaérobies à solubiliser, dégrader et produire de grandes quantités de biogaz à partir d'une grande variété de matières organiques. Dans un environnement contrôlé, la DA assure une élimination appropriée des matières organiques conduisant à une réduction des émissions de gaz à effet de serre et des odeurs nauséabondes pouvant affecter la population environnante. L'objectif principal de ce travail était « d'encourager la fabrication et l'utilisation d'énergies renouvelables grâce à la production à petite échelle de biogaz dans une zone urbaine comme Yaoundé pour un mode de vie durable ». Ce travail a été réalisé à l'aide de questionnaires, d'entretiens, d'analyses en laboratoire et d'études antérieures sur la gestion des boues de vidange (GBV). Ce travail couvrait les aspects environnementaux, économiques et énergétiques liés à la gestion des FS dans un foyer ou une institution d'au moins six (6) personnes. L'étude a montré qu'une estimation de 72,35 kg de déchets est produite quotidiennement dans cette maison ou institution. Ces déchets ont la capacité de produire 1151,11 litres de méthane par jour équivalent à 0,58 kg de gaz de pétrole liquéfié (GPL), ce qui est supérieur à la quantité moyenne de gaz de cuisine utilisée quotidiennement par cette maison ou institution. Le dimensionnement des différents composants du système de biogaz a été basé sur le fait que le digesteur anaérobique utilisera une alimentation semi-solide, fonctionnera en mode semi-continu et emploiera l'utilisation des bactéries thermophiles avec la possibilité de recycler le digestat dans un milieu digesteur à dôme. L'estimation de l'investissement dans le projet a été déterminée a 600,000 FCFA avec le coût annuel pour l'exploitation et la maintenance inclusif. L'investissement a un indice de rentabilité de 1.13 sur une période de 15 ans montrant qu'il s'agit d'un projet à valeur ajoutée. L'entreprise aura besoin d'une période de 6.5 ans pour récupérer l'investissement initial dans le système. Sur la base de l'évaluation, la digestion anaérobie est une technologie de traitement faisable et viable pour les FSM.

Mots clés : Digestion anaerobique, biogaz, boues de vidange, énergies renouvelables, Yaoundé.

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LIST OF ABBREVIATIONS AND ACRONYMS

AD	Anaerobic Digestion
BOD	Biochemical Oxygen Demand
CH_4	Methane
CO_2	Carbondioxide
COD	Chemical Oxygen Demand
CHP	Combined Heat and Power
CSTR	Continuous Stirred Tank Reactor
DA	Digestion Anaerobique
FA	Free Ammonia
FS	Faecal Sludge
FSM	Faecal Sludge Management
GBV	Gestion des Boues de Vidange
GHG	Greenhouse Gases
h_{int}	Internal height of the cone
$H_{external}$	External height of digester
Hint	Total internal digester height
HRT	Hydraulic Retention time
Mi	Initial mass before drying
Mf	Final mass after drying
MARPOL	Marine Pollution
MDGs	Millennium Development Goals

MINEPDED	Ministry of Environment, Nature Conservation and Sustainable Development
MINIMIDT	Ministry of Industry, Mines and Technical Development
MINEE	Ministry of Water and Energy
NH_4	Ammonium ion
OLR	Organic Loading Rate
OM	Organic Matter
Pa	Average daily production of biogas
PNGE	National Environment Management Plan
Q	Flow rate
Qm	Daily production of methane
Rint	Internal radius
SDGs	Sustainable Development Goals
THP	Thermal Hydrolysis Process
TS	Total Solids
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
Vcone	Volume of cone
Vcylinder	Volume of cylinder
Vg	Volume of the gasometer
Vt	Total volume
VFA	Volatile Fatty Acids
WTE	Waste to Energy

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GENERAL INTRODUCTION

The incredible economic and industrial growth in the past couple of centuries has made the human society to reach new limits of science and technology, while providing the necessary resources for a comfortable and an abundant lifestyle for an increasing portion of the global population. Even with a present population of 7.8 billion people and a projection of about 11.2 billion people by 2100 (UN, 2019), these fuels are still powering a lot from our homes, industries and we have only become increasingly dependent on them with time (Akash Som Gupta, 2020). The question that has been a preoccupation now is how long we can continue on this path of consumption and use our natural resources in such indiscriminate manner.

Global warming being the best known environmental problem connected to human activities is caused by emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). It should be known that CH_4 has 25 times the impact of CO_2 on global warming. There are also increasing global problems relating to the acidification of water and soil, as well as eutrophication. The acidification of soils can lead to decreasing soil quality and reduced crop yields. Acidification in oceans is a result of more CO_2 dissolving in the water, thus lowering the pH, which affects e.g. corals (Hoegh-Guldberg et al., 2017). Eutrophication is occurring in many of the world’s lakes, coastal areas and rivers, and is mainly caused by emissions of nitrogen and phosphorus.

The UN’s 17 Sustainable Development Goals (SDGs), which were adopted by all members of the United Nations in 2015, are the blueprint for a more sustainable future (UNDESA, 2015). Renewable energy through biogas production contributes to at least 3 of the SDGs namely; life on land, climate action and affordable and clean energy. Insufficiency of petroleum products and the grossly rising problems associated with deforestation in developing countries scare the supply of energy across countries worldwide (Adalbert, 2019).

Many African countries are very much affected as a great portion of the population tends to depend on firewood for energy supply resulting in the cutting of trees without replanting in most cases. They do this regardless of the disadvantages it causes to their immediate environment. Cooking and heating with solid fuels create harmful smoke and particles that fill homes and the surrounding environment. Long term exposure to these fine particles in the air contributes to a range of health effects such as; respiratory diseases, lung cancer and heart disease (index mundi, 2019). Children and elderly are most the most infected in such scenarios.

Also, with growing consensus amongst global leaders and policy makers about the importance of sustainable development, the focus is on shifting to low-carbon societies and Circular Economy as primary economic and environmental ideologies. The Circular Economy is defined as “a regenerative system which minimizes resource input and wastage, emissions, and energy usage and leakage by slowing, closing, and narrowing energy and material loops” (Geissdoerfer et al., 2017). Thus, implying a focus on reducing waste to a minimum, and recovering useful resources from the waste streams generated from social and industrial activities. These recovered resources can be used by creating more value for the stakeholders. The concept of Circular Economy has been recognized globally, with policy makers and governing agencies integrating it into local, national, and international policies.

Problem Statement

In Cameroon, as is the case for other developing countries, towns and cities have set backs as the faecal sludge of the inhabitants is grossly mismanaged. In Yaoundé, homes and institutions either have a septic tank or just a pit where faecal sludge is ejected. The process of management of this waste formed by a lot of inhabitants is a cause for concern as most people do not share in the vision of a sustainable development. Faecal sludge from the septic tanks and pits in some cases is extracted by special trucks and transported to the landfill where it creates a whole other level of air, underground water and soil pollution with the emission of harmful gases (CH_4, CO_2, ammonia, nitrogen oxides, etc), leachate and excess nutrients(nitrogen and phosphorus).

In the rest of the cases, the faecal sludge is emptied into holes dug for this task thus polluting the soil and underground water. Not forgetting the emission of harmful gases from the pit latrines. It should be noted that among the other savage methods of managing faecal waste, these two are the most used whereas faecal sludge is a very valuable waste to recycle. Not forgetting that the improper disposal of faecal waste brings health issues to the people of its immediate environment: malaria from mosquitoes, typhoid from contaminated water, lung diseases from pungent the odors and so on.

Majority of the African population lacks access to sustainable energy, many countries of which depend on traded energy. Cameroon with this massive vision could comprise exploitation of its resources forging towards replying to the currently increasing energy demand, private sector development, poverty eradication, financial issues inclusive and so on. Biogas technology has been showed to link many components as it could be operated based on a good variety of daily waste available for transformation into a useful form.

Cameroon shares the same problems with other African countries as a lot of people do not have enough energy access for their daily life activities and they depend much on traditional biomass like firewood, solid waste (especially plastics), agricultural products, animal waste and petroleum products in order to fulfill energy demand for cooking and other purposes. This can be disadvantageous to the environment not forgetting humans as these traditional fuels release harmful gases which could most likely have adverse health effects, carry ineffective energy and is difficult to manage the amount of their heat released. Poverty nevertheless is contributing to a burden on the development of the country.

Cameroon is blessed with a vast potential of energy resources but their level of valorization is deplorable causing immediate energy challenges implying the need for alternative, affordable and reliable sources of energy to meet this gap. This study, therefore, reviews and assesses the prospects and sustainability of biogas production from faecal sludge in Yaoundé, Cameroon. It will therefore be essential to depict some fundamentals of biogas production and also assess the biogas resource potential of the said area of concern in the country.

This study also plays a part to a promising future for biogas production in Cameroon given its vast and increasingly growing population implying immediate faecal sludge availability. However, the proliferation of this technology in the country is hindered by the lack of appropriate institutions, policies, regulations, incentives, political will and engagements, technicians and appropriate funding mechanisms with respect to the alarmingly growing population. The promotion of biogas production in Cameroon is currently done by mostly local and international NGOs with limited state engagements.

Research Question

How can biogas formation from faecal waste be a method to promote the production and use of renewable energy?

Research Objectives

- Main Objective:
  This thesis has as main aim, to encourage the making and use of renewable energy through small scale production of biogas in an urban area like Yaoundé for a sustainable living.
- Specific Objectives
  - ✓ To examine the former and current methods of faecal sludge management in Yaoundé.
  - ✓ To quantify the energy potential from faecal sludge decomposition in an anaerobic process.
  - ✓ To evaluate the possibility of a cost effective cooking gas system from biogas in different structures of Yaoundé.

The main focus during this research was studying how to valorize faecal waste in both large scale and small scale while pointing out at the same time the benefits of renewable energy as a sustainable way of living. Taking into account previous faecal waste management methods for the past decades, faecal sludge would be assessed as a tool for future valorization of its kind and construction of sewage treatment plants in other parts of our nation Cameroon as it is not a bone of contention for only one area.

Structure of the work

This thesis contains a general introduction, 3 chapters and a general conclusion.

- The General Introduction stating the problem and objectives of this thesis.
- Chapter 1 is the literature review with emphasis on the process of anaerobic digestion and also cooking gas generation from biogas.
- Chapter 2 presents the material and methods including the study area, it's physical and environmental conditions.
- Chapter 3 consists of the presentation of collected data, analysis, results and discussions.
- A general conclusion as well as suggestions and perspectives.

CHAPTER 1: LITERATURE REVIEW

Introduction

The objective of this review is to bring out the generalities of anaerobic digestion and renewable energy and to provide an overview of the various writings on the treatment and energy recovery of faecal sludge and the production of cooking gas from biogas. In general, it will be a question of defining and presenting the key concepts and assessing the work already done as far as they are concerned.

1.1. DEFINITIONS OF SOME CONCEPTS

1.1.1. Waste and waste management

Under the Waste Framework Directive 2008/98/EC article 3(1), the EU defines "waste as a left over, a redundant product, or a material of no marginal value for the owner and which the owner discards, intends to discard or is required to discard".

According to the Cameroonian Law No 96/12 of 05th August 1996 relative to the Framework Law on Environmental Management, "waste is any residue from the production, processing or utilization process, any substance or material produced or, more generally, any movable and immovable goods abandoned or intended to be abandoned". There is no universally accepted definition for waste. These definitions above suggest that waste depends on time, location, culture and social conditions, in other words, waste reflects our life and varies with space and time.

Also, waste considered by someone is not necessarily waste to another as UNESCAP, 2000 states, 'waste can be considered as those materials no longer required by an individual, institution or industry'. The European Waste Catalogue states, that waste is categorised in two major forms: hazardous and non-hazardous waste and also based on the source with over twenty different categories and about eight hundred and twenty four sub-categories (Lavagnolo, 2018). Category 20 of this catalogue explains that municipal waste consists of household waste and similar commercial, industrial and institutional waste. Waste management includes all activities and actions required to manage waste from its interception to its final disposal.

It includes; collection, transport, treatment and disposal of waste together with monitoring and regulation of waste management process (Waste management). Waste is produced by human activity from the extraction and processing of raw materials and it can be solid, liquid or gas. Each type requires different methods of disposal and management as they pose different health threats to human health and the environment. Waste management therefore is intended to reduce these adverse effects on human health, environment and aesthetics.

The concept of waste management was first brought up by the prefect of Paris Eugene Poubelle in November 1883 who obliged all building owners to obtain special containers of a hundred and twenty litres capacity equipped with lids in order to deposit the garbage. This was due to the constant increase of population in the city and continuous littering of waste all around.

1.1.1.1. Waste management hierarchy

This is a tool used to evaluate the processes for environmental protection alongside resource and energy consumption and establish preferred program priorities based on sustainability. It indicates the order of preference for action to reduce and manage waste and its usually preferred diagrammatically in the form of a pyramid. The aim of the waste hierarchy is to extract the maximum practical benefits from products and to generate the minimum amount of waste. The figure below shows the waste management hierarchy.

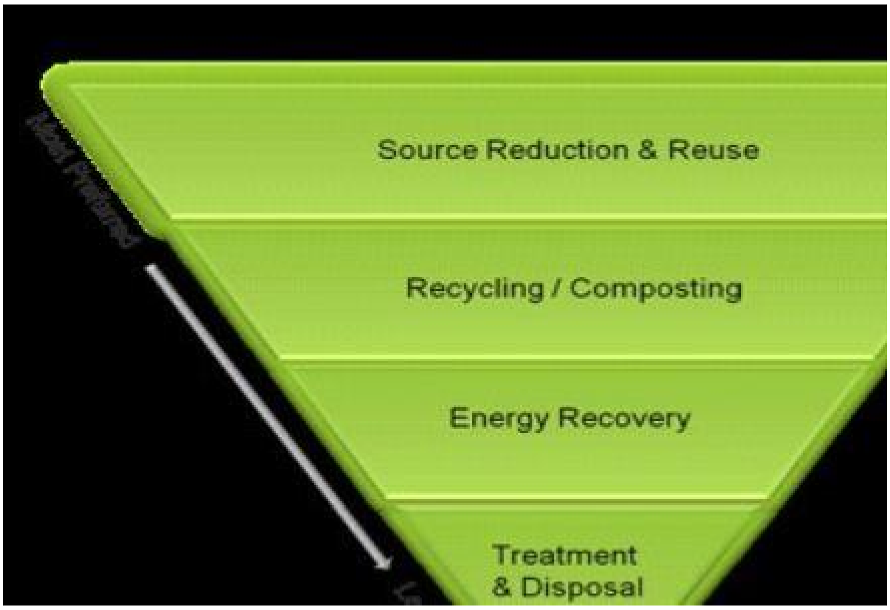

Figure 1: Integrated waste management hierarchy

(Lavagnolo, 2018)

- **Source reduction and reuse**

This refers to waste prevention, which means, reducing the waste at the source. According to Lavagnolo 2018, it can take different forms including; reusing, reducing packaging, buying in bulk, redesigning products and reducing toxicity. Source reduction is as important in manufacturing. Source reduction can; save natural resources, conserve energy, reduce pollution and reduce waste toxicity.

- **Recycling/composting**

"Recycling is a series of activities that includes the collection of used, reused or unused items that would otherwise be considered waste; sorting and processing the recyclable material into raw materials; and remanufacturing the recycled raw materials into new products" (Lavagnolo, 2018). Recycling prevents the emission of greenhouse gases and water pollutants, saves energy, supplies valuable raw materials to industries, creates jobs, stimulates the development of greener technology, conserves resources for future generations and reduces the need for new landfills and incineration.

- **Energy recovery**

Energy recovery is the conversion of non-recyclable waste material into usable heat, electricity or fuel through a variety of processes including anaerobic digestion, combustion, incineration, gasification, pyrolysis and landfill gas (LFG) recovery (EPA). This process is also called waste to energy WTE.

- **Treatment and disposal**

Landfills are the most common form of waste disposal and are an important component of the integrated waste management system. Landfilling is the burial of municipal solid waste. It is the last stage of the life cycle of waste that can't be recycled or reused. Landfills for municipal solid waste are generally regulated according to national standards by the state or local governments. This is as a result of certain environmental and health hazards which originate from the presence of landfills in certain localities. In order to avoid such negative impacts, stringent regulations for landfill design, leachate management, leachate gas ventilation, closure and post closure monitoring and restoration of these areas have been implemented. These landfill regulations have led to the elimination of many existing open dumps in certain countries.

1.1.2. Bioenergy

Bioenergy is renewable energy produced from natural and biological sources that range from plants and timber to agricultural/food waste and animal waste (sewage) (Mckendry, 2002a).

1.1.3. Biomass residue

Biomass regroups a variety of organic material of plant and/or animal origin that can be exploited for bioenergy production. It can be purposefully grown energy crops, waste from food crops and agriculture, food processing and animal farming, human waste from sewage plants and wood or forest residue (for example sawdust) (Sanke & Reddy, 2008). The waste collected from activities involving plants and animals as well as forest or wood can be collectively classified under biomass residue. Biogas production systems are more than just waste management systems or the production of renewable energy. To grasp more of the benefits of biogas production systems, systems analyses need to be carried out from different points of view. One way could be to study the resource efficiency of biogas production systems. Resource efficiency implies that greater value can be delivered with less input. Also those resources can be used in a more sustainable way and that the impact on the environment can be minimized, as well as minimizing waste.

1.1.4. Stakeholder

This is any group, organization or individual that can influence or be influenced by the sanitation services under consideration and that has a vested interest in the sanitation sector (covering off-site or on-site sanitation services). Stakeholders may be grouped into the following types of categories: international, national, local, political, public / private sector, non-governmental organizations (NGOs), operators and users / consumers (SFD MANUAL, 2018).

1.1.5. Sustainability

This term is synonymous to continuity, maintenance and the capacity to endure over an extended period of time. Sustainability as a concept is supported by four pillars; environment, economy, social and inter-culturalism (most recently added). With respect to biofuels sustainable/sustainability means biofuel activities will be done within the limits of these four pillars without jeopardizing the potential for future generations to meet their own needs (Ekins *et al.*, 2008) quoted by (Ndobe, 2014).

1.1.6. Renewable energy

Renewable energy is one derived from natural sources that replenish themselves over short periods of time. That is, renewable sources. They are virtually inexhaustible and non-depletable sources; these sources are often referred to as non-conventional sources (Ndobe, 2014). Examples include the sun, running water bodies such as rivers, wind, rain, plants, algae, organic wastes and even the Earth's heat (geothermal).

1.2. FAECAL SLUDGE AND BIOGAS PRODUCTION IN CAMEROON

1.2.1. Different faecal sludge definitions

- Cesspit: An enclosed container used for storing sewage.
- Combined sewer: A sewer system designed to carry both blackwater from homes and rain water. Combined sewers are much larger than separate sewers as they have to account for increased volumes.
- Faecal sludge: The general term given to undigested or partially digested slurry or solids resulting from storage or treatment of blackwater or excreta.
- Faeces: Refers to (semi-solid) excrements devoid of urine or water.
- Septage: Liquid and solid material pumped from a septic tank, cesspool or other primary treatment source (Bellagio, 2005).
- Sewage: General term given to the mixture of water and excreta (urine and faeces). It could also be referred to as blackwater which is a better way of addressing it.
- Sewer: An open channel or closed pipe to convey sewage.
- Sewerage: All the components of a system to collect, transport and treat sewage (including pipes, pumps, tanks etc).
- Sludge: The thick, viscous layer of materials that settles to the bottom of septic tanks, ponds and other sewage systems. Sludge comprises mainly organics but also sand, grit, metals, and various chemical compounds.

1.2.2. General environmental impacts of faecal sludge

Faecal sludge comprises all liquid and semi-liquid contents of pits and vaults accumulating in on-site sanitations in stallations, namely unsewered public and private latrines or toilets, aqua privies and septic tanks. These liquids are normally several times more concentrated in suspended and dissolved solids than wastewater (EAWAG, 2008).

Some individuals offer manual emptying, traditionally carried out with buckets where the emptiers step into the vault or pit to evacuate the sludge that has generally solidified to be scooped out. Hence, traditional manual emptying is associated with considerable health risks for the emptiers. The general public is also at risk as the emptied sludge is usually deposited into manually dug holes or water bodies. There are as well toilets that are directly connected to water bodies in which all the waste is deposited.

A fee is usually charged by private collectors for each load of FS delivered to the discharge site when one is available and as a consequence, some inhabitants often prefer to dump the waste in non-designated sites to avoid paying the collection fee. Mechanised emptying vehicles are more cost-intensive but also more hygienic and efficient. Due to the narrow streets in poor urban settlements, they often cannot access the pits.

The total lack or inadequate treatment of faecal sludge could imply the following impacts:

- Health impacts
    - The primary hazard is pathogen exposure from untreated or insufficiently treated faecal excreta transmitted via the faecal oral route.
    - Helminths are parasitic worms that infect and live off a host. Helminths eggs such as ascaris are abundant in faecal sludge (Yen-Phi *et al.*, 2010; Koné *et al.*, 2007) and can have devastating effects on human health, particularly in children. Ascaris eggs are hard and can survive for long periods in soil and pit sludge. The bulk of helminthes eggs contained in faecal sludges end up in the biosolids generated during treatment. Direct contact with contaminated material and subsequent accidental ingestion from contaminated fingers or utensils are major transmission pathways. Contact may occur before treatment, during treatment, including handling or when the material is used/applied to soil. It should also be known that ascaris eggs are an important indicator of faecal contamination, given their persistence in the environment.
    - The most common pathogenic protozoa in human stools are Giardia, Cryptosporidium spp., Dientamoeba fragilis, Entamoeba spp. (including nonpathogenic species), Blastocystis spp., and Cyclospora cayetanensis (Fletcher *et al.*, 2012). Infections from protozoa are a main cause of gastrointestinal illnesses and waterborne diseases worldwide (McHardy *et al.*, 2014).
    - Moreso, contamination of food may occur directly from use but also through unhygienic practices in the kitchen. Even if the fertilised crop is cooked before

consumption, surfaces may be contaminated and pathogens transferred to other foods or fluids.

- Impacts on soil

Salts, heavy metals, persistent organic compounds, hormones, and nutrients are relevant substances in terms of environmental impact on soil:

  - Metals are bound to soils at a pH exceeding 6.5 and/or with high organic matter content. If the pH is below this value, if organic matter is consumed or if all feasible soil adsorption sites are saturated, metals become mobile and can be absorbed by crops and contaminate water bodies.
  - Nutrients in sludge can accelerate the process of soil salinisation in arid and semi-arid regions.(WHO, 2006).

- Impacts on water bodies

Nutrients in faecal sludge may percolate to groundwater if applied in excess or if flushed into surface water after heavy rainfall.

  - High concentrations of biodegradable organic matter in agricultural runoff water and high nutrient values can lead to the depletion of dissolved oxygen in lakes and rivers causing the death of fishes, algae and other forms of aquatic life.

- Impacts on the atmosphere

The inappropriate methods of sludge management, unavoidable emissions of pit latrines and open dumping of faeces have the following problems:

  - Global warming resulting from CO_2 emissions
  - Changes in the ozone layer as a result of nitric oxide and nitrogen dioxide, methane, nitrous oxide;
  - Acid rain as result of sulphur dioxide and ammonia emissions;
  - Severe health conditions.

Faecal sludge is not only limited to CH_4 emissions which is a toxic gas released by the anaerobic decomposition of waste but also has a lot of impacts as are stated above.

1.2.3. Faecal waste management

Faecal sludge management is the collection, transport, treatment, and reuse/disposal of faecal sludge from pit latrines, septic tanks or from other onsite (non-sewered) sanitation systems. It is an area of growing interest in the light of global efforts to achieving the SDGs especially in developing countries as the quantities of faecal sludge to be managed are on the ascendency due to increasing populations and limited number of sewered sanitation installations in these areas. Owing to financial constraints, frequent power failures, intermittent water supply and general water scarcity, Strauss *et al.* (2003) predicted that the dependence of developing countries on onsite sanitation systems will continue to grow for decades to come. Nevertheless, several challenges are encountered in the collection and transport of faecal sludge (FS) especially in urban centres and unplanned settlements. These challenges hamper the success of FS management schemes and pose stakeholders at risk. Shown are the sanitation service chain (Figure 2-1) as adopted from Parkinson *et al.* (2013) and some highlighted causes, problems, and effects of poor FS management (Figure 2-2).

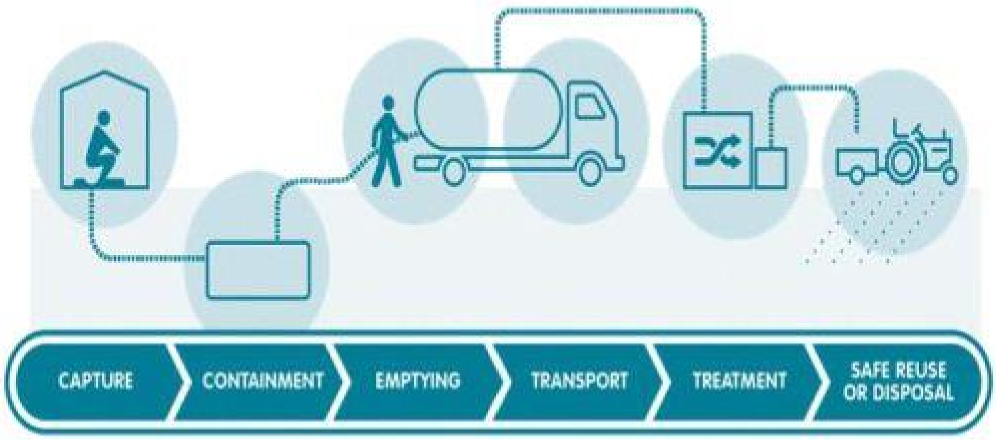

Figure 2:Sanitation service chain

(Parkinson et al., 2013)

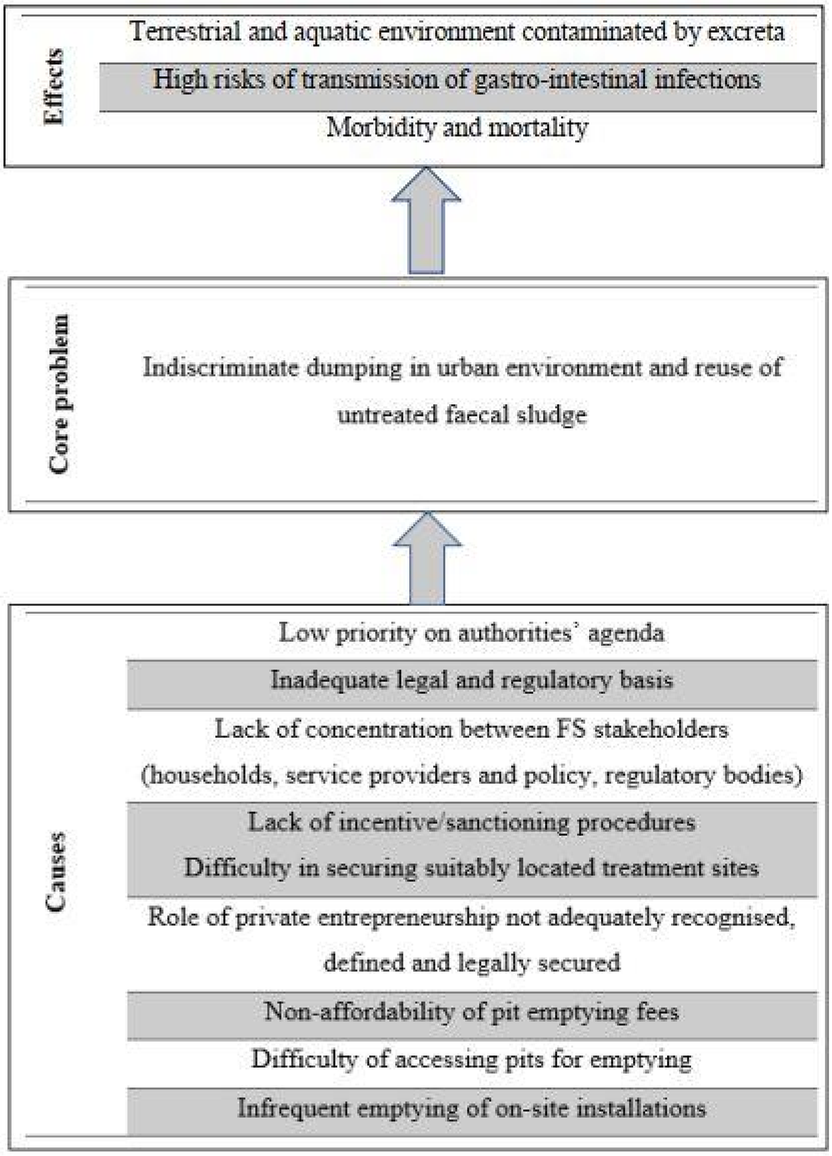

Figure 3: Present-day FS management

(EAWAG, 2009)

1.2.3.1.Containment, Collection and Transportation.

Containment is the starting point for management and there can be containment systems as follows; hybrid systems, which retain solids on-site in a tank, while discharging liquid for off-site treatment

- on-site septic tanks, which retain solids, liquid and scum, and are regularly desludged
- pit latrines, which retain faecal sludge (only solid) in a tank and the partly digested faecal sludge is removed at infrequent intervals, depending on the size of the tank

- self-contained on-site systems, which retain faecal sludge and allow its on-site transformation into a safe material, able to be removed manually.

Different variations exist within each containment cluster. Holding tanks may be fully lined with impermeable walls and an open or sealed bottom. Pits may be lined or unlined. Faecal sludge retainers prevent faeces from spreading into the environment, thereby reducing the risk of contamination. They allow for pre- and subsequent treatment and facilitate collection, quantification and transportation. However, some retainers (especially pit latrines and septic tanks) are poorly constructed and could increase the risk of surface and groundwater contamination with associated environmental and health risks (Peal *et al.*, 2013).

Sludge can be removed by mechanical means or manually: depending on the type of containment system, the local climate, access to the site, the type of equipment used by the service provider, and their level of expertise (Mikhael *et al.*, 2014). Manual collection which is the removal of faecal sludge using basic tools such as buckets, shovels and ropes is most often used by individuals with low-income and in informal settlements. Other collection methods are direct lifting, cartridge containment, and manually operated mechanical collection (sludge gulper, manually operated diaphragm pumps) (Mikhael *et al.*, 2014).

Manual collection methods have not been formally regulated in Africa. Although there are some informal associations that regulate the practice, standards for occupational health and safety are seldom enforced. The high demand for these services by low-income urban inhabitants continues to sustain the status quo. Fully mechanized emptying equipment can be mounted on a frame or trolley or directly onto the transport vehicle. Examples of mechanized methods are the motorized diaphragm pump, trash pump, pit screw auger, Gobbler, Vacu-Tug and the conventional vacuum tanker (Mikhael *et al.*, 2014). Mechanical emptying is a faster and more effcient process. It is, however, restricted to middle- and high-income households with septic tanks and watertight tanks. Vacuum trucks often transport sludge to illegal dumping sites outside the city limits rather than authorized treatment stations. The charge-out fees for emptying vary by country, region, market, volume and road condition, among other factors.

1.2.3.2.Treatment and Processing Methods

After collection, faecal sludge is usually transported to faecal sludge treatment plants, where available. Treatment starts with separating the solid from the liquid through mechanical or biological means. Biological treatment includes stabilization ponds, drying beds and constructed wetlands, while mechanical treatment involves mechanized processes such as activated sludge, up-flow anaerobic sludge blanket reactors, and anaerobic digesters. Many studies show that some faecal sludge treatment plants in Africa are not well maintained or managed and treatment performance is questionable. One underlying cause is the constant financial constraints encountered in these facilities

After treatment, faecal sludge can be recycled in several ways (Gold *et al.*, 2016; Nikiema *et al.*, 2014; Diener *et al.*, 2014). Examples include:

- Using it as compost fertilizer and biochar in agriculture.
- Converting to biogas for electricity and cooking.
- Dry sludge can be used as fuel for industries (as is done in Rwanda) and as feed for aquaculture (as done in Durban, South Africa).

1.2.4. Biogas production in Yaoundé, Cameroon

Based on World Bank's data, only 12 million out 23 million of Cameroon's population have access to electricity. Cameroon's poorest can't afford bottled cooking gas. Cameroon will derive massive economic, health and environmental benefits if renewable endeavors are spread throughout the country. According to the Ministry of Trade, a 12 kilogram container of liquefied petroleum gas costs 6,000 FCFA (Central African Francs). With the savings from using cheap biogas, families are able to use their money on other essentials like medical care and education. The use of biogas energy can help preserve and protect the country's forests to say more.

The legal framework of Cameroon is not clearly defined and also there are no existing texts on renewable energy sector in Cameroon. i.e. the lack of strong, dedicated institutions, lack of clear responsibilities, complicated, slow or non-transparent permitting procedures. Law No 2011/022 of 14 December 2011 governing the electricity sector of Cameroon gives a little attribution of renewable energy but with a lot of insufficiency

Furthermore, everyone is has a right to a healthy and clean environment in the context of the Cameroonian constitution. Environmental management and urban/rural sanitation are major political issues in Cameroon. With the current phenomena of rapid population growth, increased urbanisation, industrialization and economic development, Cameroon and Yaoundé in particular is facing a huge challenge for ecological waste management in order to ensure a sustainable environment. Waste management is governed by an arsenal of laws and regulations. This regulation ranges from laws to circulars, decrees and orders. Appendix 3 shows the legislation as well as the institutional frameworks that govern the management of waste in Cameroon.

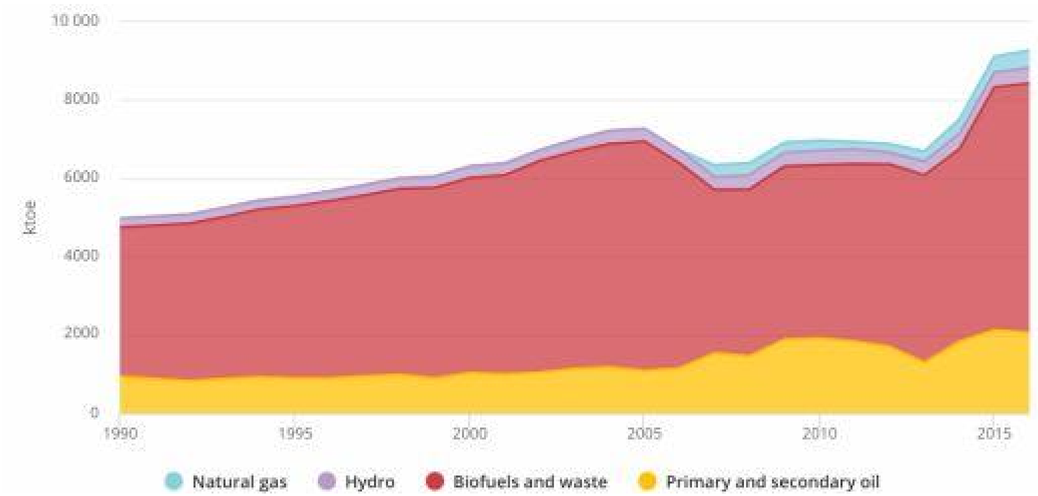

Figure 4: Total Energy Supply (TES) from 1990-2016

(IEA 2016)

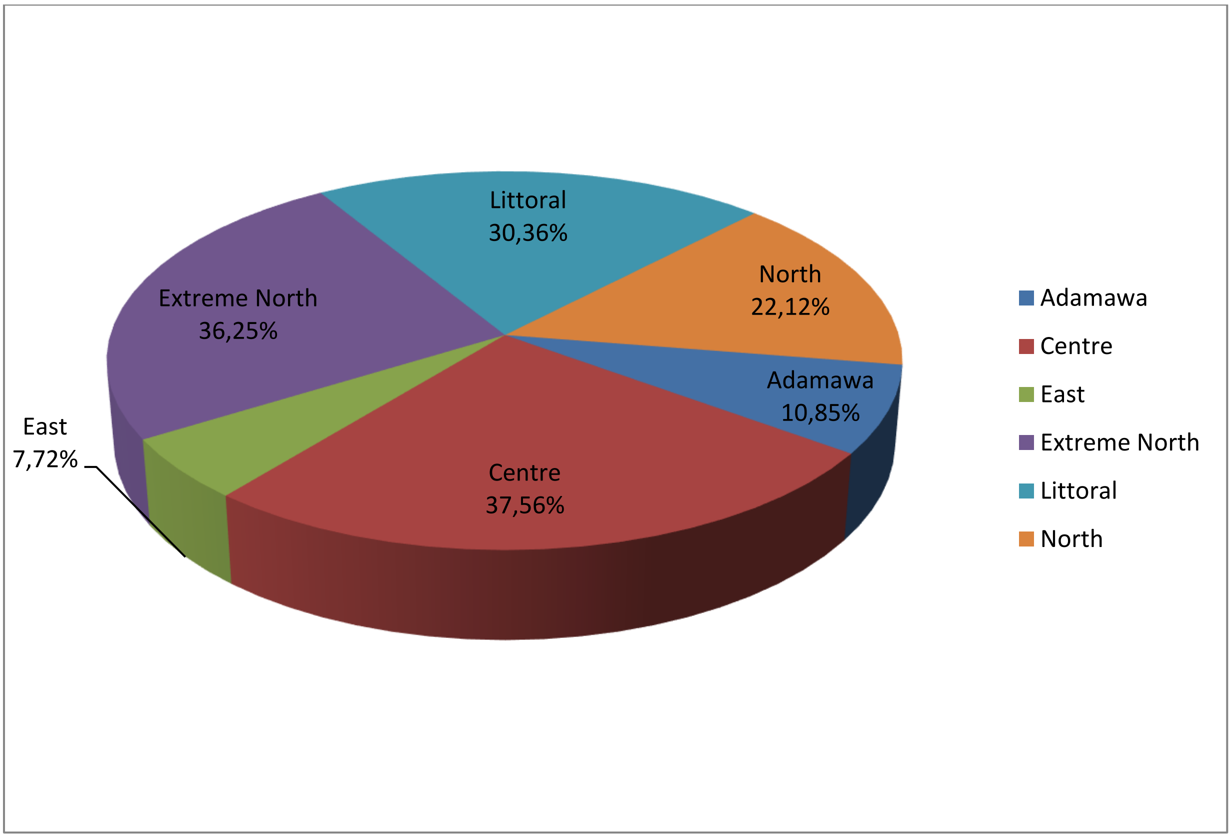

Figure 5: Graphical Abstract of Technical WtE Production Potential in Cameroon

(Nkweauseh, 2020)

1.3. ANAEROBIC DIGESTION

In many countries, sustainable waste management as well as waste prevention and reduction have become major political priorities, representing an important share of the common efforts to reduce pollution and greenhouse gas emissions and to mitigate global climate changes (NREL 2013). At the same time the worldwide drive to find clean, renewable energy sources remains a main priority. The production of biogas through anaerobic digestion (AD) of animal manure and slurries as well as of a wide range of digestible organic wastes, converts these substrates into renewable energy and offers a natural fertiliser for agriculture. This approach contributes to improve waste management practices and at the same time fulfil the goals of sustainable energy management (Monett 2003). Anaerobic digestion (AD), also referred to as bio-methanation or bio-methanisation, is the biochemical decomposition of complex organic material by various bacterial activities in the absence of oxygen (Meegoda et al, 2018). The two main products of AD are biogas, and a mixture of bacterial biomass and inert organics, often referred to as digestate or effluent.

1.3.1. History

Historical evidence indicates that the anaerobic digestion process is one of the oldest technologies. Bacteria that breakdown organic materials into biogas is some of the oldest multicelled organisms in the planet. In the eighteenth century, Flemish chemist, Jan Baptise Van Helmont discovered that decomposing organic matter produced a combustible gas. The first industrial digester was built in 1859 in India in a colony of Bombay. By 1895, biogas was recovered from a sewage plant and used to light street lamps in Exter. England. The applied research on anaerobic digestion began with Buswell in 1920, which identified the main processes of anaerobic degradation and established the associated stoichiometry.

The main purpose of producing biogas through anaerobic digestion of organic material is often to produce a renewable energy carrier that can replace fossil fuels. The European Union has launched targets for 2030 of reducing GHG emissions by 40%, relative to 1990 levels, and achieving a proportion of at least 27% renewables in the energy system (European Commission, 2014). Biogas can contribute to fulfilling both of these targets. Anaerobic digestion is also a sustainable waste management option for organic waste, in contrast to landfilling and so it is important that all waste suitable for recovery or recycling should not be landfilled.

The European Parliament in 2008 presents the waste management hierarchy, an order of prioritization for waste management. At the top of the hierarchy is the prevention of waste, followed by reuse, recycling, recovery and disposal (landfilling) at the bottom (European Parliament, 2008). The remaining solid material after anaerobic digestion is called digestate, rich in nutrients and can be used as fertilizer on farmlands. This then shows that it is possible to recover both energy and nutrient with biogas production systems. However, biogas production systems also contribute to many more benefits.

According to the Renewable Energy Directive (the RES Directive) (European Parliament, 2018b), biogas production can contribute to a sustainable development. The RES Directive promotes biogas as an option in the transport sector to reduce greenhouse gas emissions in the European Union (European Parliament, 2018b). Anaerobic digestion of organic waste can reduce greenhouse gas emissions as well as water, soil and air pollution, compared to landfilling. Biogas can also contribute towards innovations, jobs and economic growth, as well as reducing reliance on energy imports.

1.3.2. Processes involved in anaerobic digestion

- **Hydrolysis**

This is the first stage of the degradation process and it is considered the rate determining step as it’s usually the slowest of the four. The bacteria transform complex organic materials into liquefied monomers and polymers; i.e. proteins, carbohydrates and lipids (fats) are transformed to amino acids, monosaccharides and fatty acids respectively. This extracellular enzymemediated transformation of higher mass organic molecules into basic structural building blocks is very important as particulate organic materials are simply too large to be directly absorbed and used by microorganisms as substrate / food source. The microorganisms involved in the secretion of enzymes that hydrolyse these macromolecules can be represented by Clostridium sp., Proteus vulgaris, Bacteroides sp., Bacillus sp., Staphylococcus sp., Micrococcus sp or Vibrio sp.

- **Acidogenesis**

In the second stage, acidogenic bacteria convert the soluble organic monomers of sugars and amino acids to ethanol and acids (such as propionic and butyric acid), acetate, H2 and CO2. The degradation of amino acids also leads to production of ammonia. The bacteria involved in this step include; Lactobacillus sp., E. coli, Staphylococcus sp., Bacillus sp., Pseudomonas sp., Micrococcus sp., Clostridium sp., Acetobacterium sp. These bacteria have a rapid growth rate about thirty times that of methanogenic populations and have the ability to live in extreme conditions, especially at low pH from 4.5 to 6.3 (Li et al., 2011).

- **Acetogenosis**

In this third stage both long chain fatty acids and volatile fatty acids and alcohols are transformed by acetogenic bacteria into hydrogen, carbon dioxide and acetic acid. Hydrogen plays an important intermediary role in this process, as the reaction will only occur if the partial pressure is low enough to thermodynamically allow the conversion of all the acids. The microorganisms carrying out these transformations are represented by Syntrobacter wolinii, Syntrophomonas wolfei, Pelotromaculum, thermopropionicum, Clostridium aceticum, Mithella propionica.

- **Methanogenesis**

During this final stage, methanogenic bacteria convert the hydrogen and acetic acid to methane gas and carbon dioxide. Methanogenesis is affected by conditions in the reactor such as temperature, feed composition and organic loading rate. Two major groups of bacteria are defined in this step, the acetotrophic methanogens and the hydrogenotrophic methanogens. The figure of the anaerobic digestion scheme is shown below.

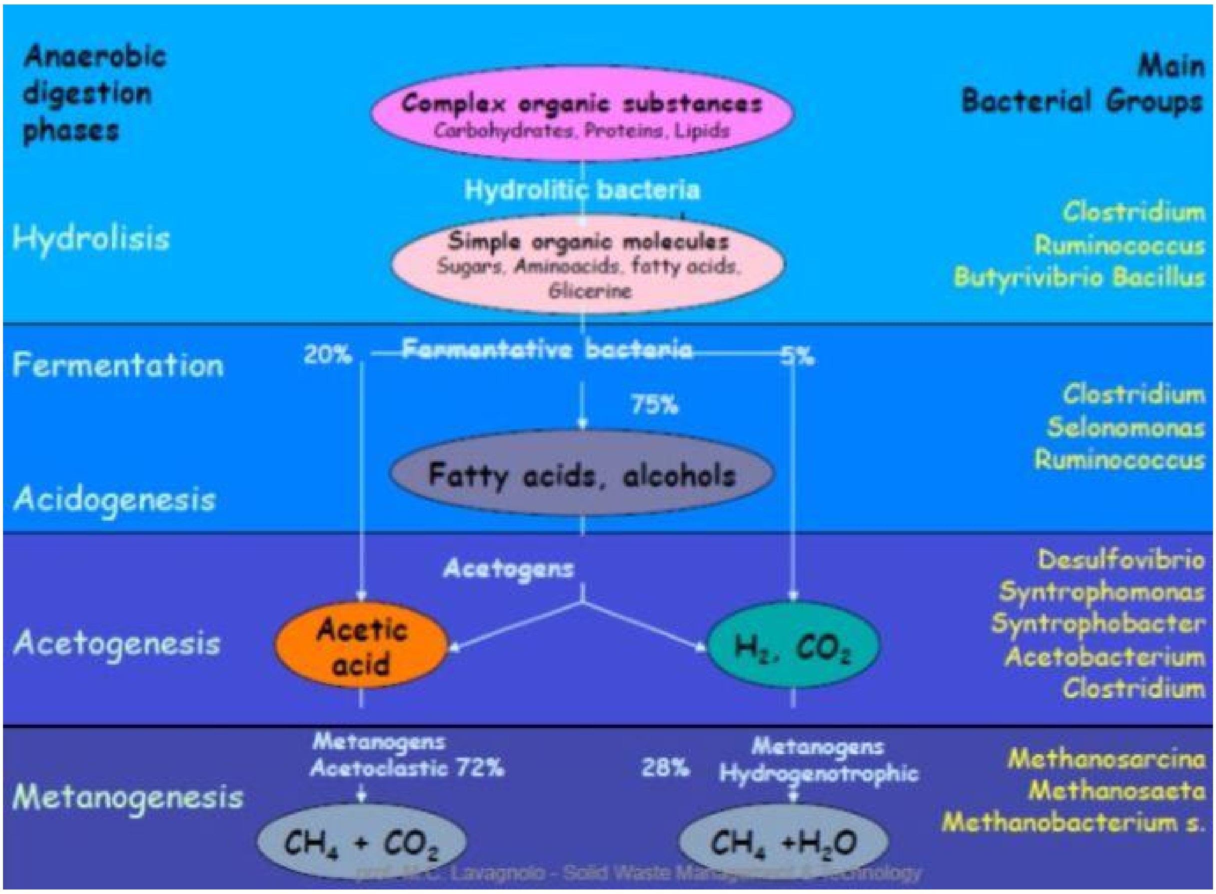

Figure 6: Figure 2: Simplified scheme of anaerobic digestion

(Lavagnolo 2018)

The gaseous product, biogas, consists mainly of methane (CH_4) and carbon dioxide (CO_2), but also contains several other gaseous "impurities" such as hydrogen Sulphide (easily detectable by its smell of rotten eggs), Nitrogen, Oxygen and Hydrogen (see Table 2). Biogas with a CH_4 content higher than 45% is flammable; the higher the CH_4 content the higher the energy value of the gas.

Table 1: Typical composition of biogas from biowaste (Vögeli Y. et al. 2014)

Components	Symbol	Concentration (Vol-%)
Methane	CH_4	55–70
Carbon dioxide	CO_2	35–40
Water	H_2O	2 (20 °C)–7 (40 °C)
Hydrogen sulphide	H_2S	20–20 000 ppm (2 %)
Nitrogen	N_2	< 2
Oxygen	O_2	< 2
Hydrogen	H_2	< 1
Ammonia	NH_3	< 0.05

1.3.3. Physico-chemical parameters influencing anaerobic digestion

The rate at which the microorganisms grow is of paramount importance for the AD process. The operating parameters of the digester therefore need to be controlled so as to enhance the microbial activity and thus increase the AD efficiency. The most important parameters are described below.

- **Temperature**

Temperature plays an important role in anaerobic digestion as it directly affects the growth of microbial populations and metabolic reactions. According to Lavagnolo 2018, three temperature ranges define the modes of operation process.

o Psychrophilic with T between 5-25°C (typically ambient temperature) used for low technology treatment without heating, then has a very low cost compare to the others, but some studies carried out show that the production of biogas in this condition is the lowest

o Mesophilic with Temperature between 30-45°C (typically 30-37°C) used in many processes applications for household waste, industrial waste, and animal slurry with a high content of ammonia.

o Thermophilic with Temperature range 50-60°C, used for high yielding processes, often with more advanced process technology and where sanitation is required. This method has a high energy demand to reach the temperature so it costs a lot and at too high temperature the processes are inhibited, but it presents a very good production of biogas. The optimum temperatures of digestion may vary depending on the feedstock composition and type of digester (Monett, 2003)

- **Acidity pH**

pH is one of the key parameters influencing the development of microorganisms and metabolic reactions. Optimal pH values for the acidogenic and methanogenic phase are quite different. The processes of hydrolysis and acidogenesis occur at acidic pH levels (pH 5.5 – 6.5) as compared to the methanogenic phase (pH 6.5 – 8.2) (Khalid et al., 2011). The acetic, lactic and propanoic acids formed during the acidogenic phase tends to lower the pH which inhibits this process and can be toxic to methane forming bacteria. An alkalinity level of approximately 3000 mg /L has to be available at all times to maintain sufficient buffering capacity.

- **Water content**

The water content directly affects the production of methane from solid waste through metabolic reactions and the transport of nutrients and microorganisms (Gre et al. 2016). The diffusion of the compounds into the medium is facilitated by the presence of water. “There will be no gas production if the water content is less than 20% and there will be an optimum gas production if the water content goes from 91-98%” (Lavagnolo 2018). Thus the production of biogas is higher with organic matter rich in water. Numerous studies demonstrate the importance of recirculating and injecting this liquid phase to increase methane production (Khalid et al., 2011).

- **Organic loading rate**

The Organic Loading Rate (OLR) is a measure of the biological conversion capacity of the AD system (Meegoda et al, 2018). It represents the substrate quantity introduced into the reactor volume in a given time. OLR is expressed in kilogram Volatile Solid VS per cubic meter of reactor. VS represent the organic matter in a sample which is measured as solid content minus ash content. Studies of anaerobic treatment of bio-waste in industrialized countries describe organic loading rates in the range of 4 – 8 kg VS/m3 per day, which result in VS removal in the range of 50 - 70% (Vögeli Y. et al. 2014)

- **Carbon to Nitrogen ratio**

The relationship between the amount of carbon and nitrogen in organic materials is represented by the C/N ratio. The C/N ratio is an important factor in estimating nutrient deficiency and ammonia inhibition (Vögeli Y. et al. 2014). Optimal C/N ratios in anaerobic digesters are between 20 and 30 (Samir Kumar, 2019). A high C/N ratio is an indication of rapid consumption of nitrogen by methanogens, which also results in lower gas production meanwhile a low C/N ratio causes ammonia accumulation and pH values that may exceed 8.5. Such conditions can be toxic to methanogenic bacteria. Optimum C/N ratios can be ensured by mixing different feedstock materials, with high (e.g. organic solid waste) and low (e.g. sewage or animal manure) C/N ratios to achieve an ideal C/N ratio level as shown on table 3.

- **Hydraulic Retention time HRT**

This is the time needed to achieve the complete degradation of organic matter. The retention time varies with different technologies, process temperature and waste composition (Monett, 2003). Recommended HRT for wastes treated in a mesophilic digester range from 10 to 40 days. Lower retention times down to a few days only, are required in digesters operated in the thermophilic range.

- **Mixing**

The purpose of mixing and stirring inside the digester is to blend the fresh material with digestate and thus inoculate the fresh material with microbes. Mixing avoids temperature gradients within the digester and it also prevents scum formation. Scum in digesters result in blockage of the gas pipes, machines and devices resulting in subsequent malfunction or corrosion. Mixing and stirring equipment, and the way it is performed, varies according to reactor type and TS content in the digester.

- **Substrate characteristics**

The characteristics of solid waste can greatly influence the processes of anaerobic digestion. As the composition of substrates changes, the presence of nutrients such as protein carbohydrate and lipid also changes in the waste, thus affecting the anaerobic process of the whole system since it depends on the relative amount of those components (Glauser et al., 1987) cited by (Lavagnolo, 2016).

- **Inhibitory factors**

Anaerobic digestion is a biological process requiring optimal conditions to obtain a good degradation of the substrates and thus a good production of biogas necessary for the profitability of the installations. Inhibition of the anaerobic process depends on the concentration of the inhibitors, the composition of the substrate and the adaptation of the bacteria to the inhibitor. Deublein and Steinhauser (2011) list the following typical inhibitors: Oxygen, hydrogen sulphide (H_2S), organic acids, free ammonia, heavy metals, tannins/saponins/mimosine and others hazardous substances such as disinfectants (from hospitals or industry), herbicides, insecticides (from agriculture, market, gardens, households) and antibiotics.

- **Volatile Fatty Acids VFA**

The stability of the AD process is reflected by the concentration of intermediate products like the VFA. The VFA are intermediate compounds (acetate, propionate, butyrate, lactate), produced during acidogenesis. In most cases, AD process instability will lead to accumulation of VFA inside the digester, which can cause a drop of pH-value further leading to the loss of acidsensitive glycolytic enzymes (Al SAEDI 2008). However, the accumulation of VFA is not always expressed by a drop of pH value, due to the buffer capacity of the digester. Animal manure sometimes has a surplus of alkalinity, which means that the VFA accumulation should exceed a certain level, before significant decrease of pH value can be detected.

- **Ammonia**

Ammonia is an important nutrient, serving as a precursor to foodstuffs and fertilizers and is normally encountered as a gas, with the characteristic pungent smell. Proteins are the main source of ammonia for the AD process. Ammonium ion ($NH_4{}^+$) and free ammonia (FA) are the two forms of inorganic ammonia nitrogen in the digester (Chen et al., 2008). Too high ammonia concentration inside the digester, especially free ammonia (the un-ionized form of ammonia), is considered to be responsible for process inhibition (Al SAEDI 2008). For its inhibitory effect, ammonia concentration should be kept below 80 mg/l. Methanogenic bacteria are generally more sensitive to ammonia inhibition than acidogenic bacteria.

Table 2 : Some characteristics of faecal sludge (Bleuler et al, 2020; Issahaku et al, 2019)

Type of feedstock	Organic content	C/N ratio	DM%	VS % of DM	Biogas yield m3/kg VS	Unwanted physical impurities	Other unwanted matters

Cattle slurry	Carbohydrate, Proteins, Lipids.	10 – 25	15 – 30	70-83	0.20 – 0.5	Brittles, straw, water, wood, soil	Antibiotics, disinfectants, NH4+

1.3.4. A biogas plant

It consists of the different compartments that are required to obtain good and quality biogas which are seen on figure 7 below. These include;

- **Reception tank**

The purpose of the reception tank is to store the incoming biomass and act as a buffer tank. Reception tanks typically have sufficient storage capacity and can give off various odorous compounds. These can be extracted and cleaned with different air purification systems.

- **Reactor tank**

The reactor tank is a completely enclosed and insulated steel tank or a concrete tank covered by an airtight seal. The tank can be fitted with heating coils that warm the digesting biomass, or the heat supply can be external via a heat exchange system. The tank is equipped with a stirrer that can keep the entire volume fully agitated and thus prevent the formation of a surface crust. There is, finally, a high-pressure valve to ensure that the pressure does not become unacceptably high if the gas removal fails. At the top of the tank there is an outlet for the biogas produced. The reactor tank typically has a volume of 10-20 times the daily input of biomass for a thermophilic process and 15-25 times the daily input for the mesophilic process (Jørgensen,2009).

- **Effluent discharge pump**

This is a pump that moves the digested biomass to the storage tank.

- **Digestate storage tank**

The purpose of the storage tank (or secondary digester) is to act as a buffer tank before the digested biomass can be transported away to be applied as fertiliser directly on farmland. The tank is usually covered, partly to prevent the entry of rainwater and partly to prevent the loss of ammonia. Some amount of gas can be produced in the storage tank as the biomass will never be completely digested. This gas can also be extracted and used.

• **A gas system**

This system comprises of a gas condensation for removal of water vapor, gas purification for removal of hydrogen sulphide and carbon dioxide, gas storage to store the pure biogas produced.

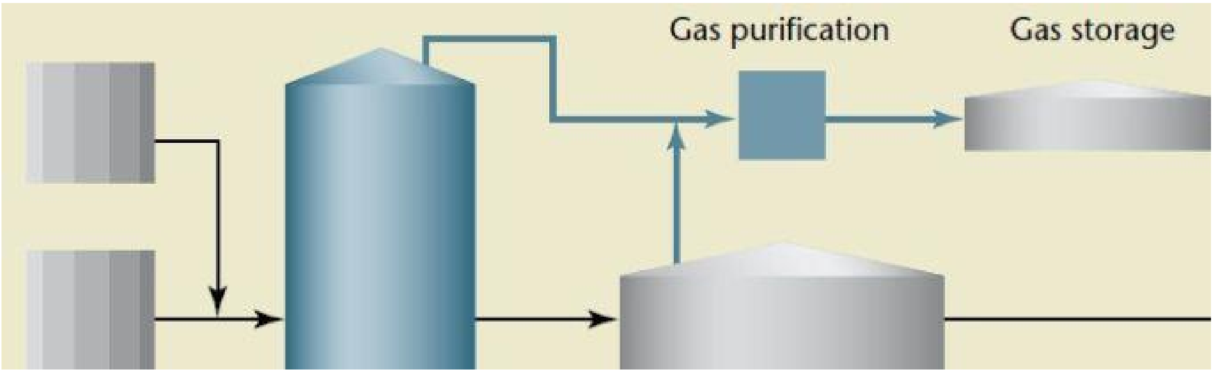

Figure 7: Schematic diagram of a biogas plant

(Somboon et Al, 2013).

1.3.5. Classification of AD reactors

Numerous AD technologies for the treatment of bio-waste have been developed worldwide and the decision maker is confronted with an extensive number of technical options from which to choose. Biogas systems can be classified according to critical operating parameters and elements of reactor design. The table below shows the different classifications for developing countries.

Table 3: Configurations of AD reactor based on some features (Lavagnolo, 2018)

Temperature	Mesophilic (33 – 45 oC)
	Thermophilic (55 – 60 oC)
Quantity of process step	One stage
	Two stage
Material flow	Batch process (discontinuous)

	Continuous process
	Quasi continuous process
Water content	Dry fermentation, < 75%
	Wet fermentation, > 75%

1.3.5.1.Continuously Stirred Tank Reactor CSTR

In a continuous feeding mode, new feedstock is added at regular intervals while an equivalent volume of slurry leaves the digester, thereby providing a continuous process of digestion. Traditionally, most biogas plants in developing countries are operated in continuous mode (Jørgensen 2009). The CSTR has the advantage that it can treat biomasses with a relatively high dry matter content under constantly stable conditions. To make room for the new biomass input, some material has to be pumped out first, and due to the continuous stirring, this means that some of the recently added, fresh biomass is pumped out again too quickly and before it is fully decomposed, which is the greatest drawback with this type of reactor.

1.3.5.2.Batch reactor

In batch-fed digesters, the reactors are filled with a feedstock, closed and left for a period of time (i.e. the retention time), then opened again and emptied (Khalid et al., 2011). Vandevivere et al. (2003) state that batch systems represent the lowest-technology of all systems and are also the cheapest. Due to their simple design and lower investments costs, batch systems are recommended for application in developing countries. However, experience shows that these reactors have some serious limitation including high fluctuations in gas production due to opening and closing after each batch sequence and variations in gas quality.

1.3.5.3.One stage fermentation

Here, all the processes take place in one reactor, and it is difficult to control the pH and temperature specific to each type of bacteria (hydrolytic, acidogenic, acetogenic and methanogenic) and can either be wet or dry. Wet bioreactors have a TS content of 16 % or less and are better applicable to organic waste/streams with high COD content with the dilution of peaks of organic concentration of toxic substances. This process is also quite sensible to toxic substances or over-loading and separation of phases is difficult. Semi-dry and dry bioreactors the TS content ranges between 22 and 40 % and require a smaller reactor volume, lower energy requirements (if heating is required), and minimal material. OLR is generally high and pre-treatment cost is reduced but there may be a difficulty to dilute toxins and instability in the process due to high OLR.

1.3.5.4.Multi stage fermentation

In a conventional fermenter, acidogenesis and methanogenesis take place in the same tank, and the acids are produced and consumed at the same rate. In case of organic overload, or in the case of substrates difficult to degrade, it may happen that the acidogenesis generates the acids more quickly than the methanogenic bacteria can not eliminate them. This is explained by the fact that each bacterium needs specific environmental conditions for their optimal growth and methanogenic bacteria are therefore the most sensitive. In this case, typically, two reactors are used, the first for hydrolysis/liquefaction and acidogenesis and the second for acetogenosis and methanogenesis (Monnet, 2003). This is to enable flexibility to optimize the products of each of these processes. The two reactor process permits a certain degree of control of the rate of hydrolysis and methanogenesis. The main advantage of two stage systems, is the greater biological stability it affords for rapidly degradable waste.

Several technologies are marketed for the treatment of organic residues among which are; Kompogas, Valorga, Dranco, Cambi thermal hydrolysis process (THP), Lipp, BTA technologies.

Several studies have been done with the aim of comparing these waste different technologies and it’s represented on the table 4 below

Table 4: Comparison between one stage commercial anaerobic digesters (Zhang et al, 2008)

Reactor Type	**KOMPOGAS**	**VALORGA**	**DRANCO**
Country of incorporation	Switzerland	France	Belgium
Establish year	1980	1982	1992
Number of plants	**38**	**22**	**17**
Capacity (ton/year)	1,000 – 110,000	10,000-270,000	3,000-120,000

Advantages	- Can deal with organics have solid content doesn't exceed 30%- Full waste stabilization and hygienisation. -Stable biogas production. Digestate free of pathogens due to thermophilic conditions. Avoiding shortcircuiting of organic waste.	This technique does not require a large land area. Baffles sustain a good contact and avoid dead zones. High net gain energy with high methane content gas.	- Tolerate high solid wastes to the range of 30- 45% and high organic loading rates of 5- 8kgVS/m3/day. Small reactor volumes. Vertical reactor avoiding waste accumulation. Minimum surface area required for reactor installation. Easy to operate with no mixing or gas injection. Thermophilic operation which avoid pathogens formation.
Biogas yield (m3/kg)	0.08 – 0.16	0.103	0.11-0.14
Retention time (days)	18-23	15-30	20
Mode ºC	55ºC	37 – 55ºC	55ºC

1.3.6. Biogas properties

Biogas is a combustible mixture of gases. It consists mainly of methane (CH_4) and carbondioxide (CO_2) and is formed from the anaerobic bacterial decomposition of organic compounds. (Jørgensen 2009). Methane is a colorless and odorless gas with a boiling point of -162°C and it burns with a blue flame. Methane is also the main constituent (77-90%) of natural gas. Methane belongs to alkanes group and is the simplest possible form of these. At normal temperature and pressure, methane has a density of approximately 0.75 kg/m3. If biogas is mixed with 10-20% air, you get explosive air, which – as the name indicates – is explosive! (Jørgensen 2009).

1.3.7. Applications of biogas

The production of biogas from AD is widely used by modern society for the treatment of livestock manure and slurries. The aim is to produce renewable energy and to improve their fertilizer quality. The figure below shows the biogas and uses.

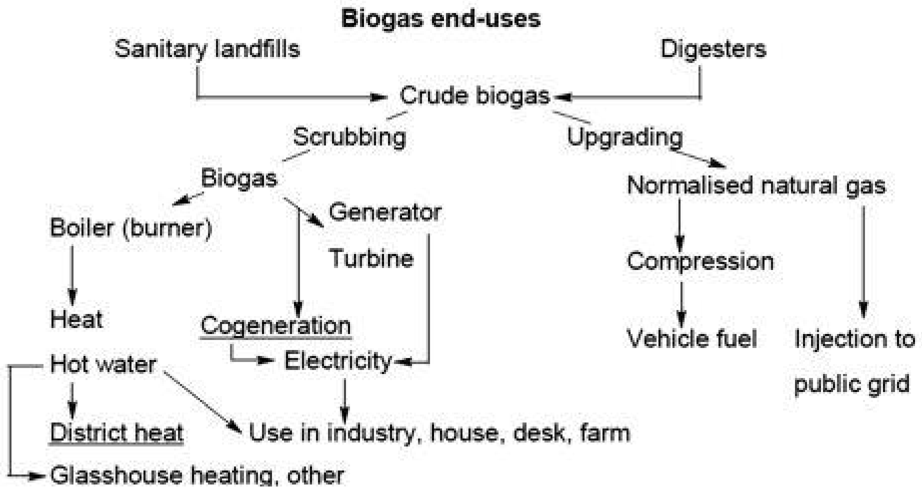

Figure 8: Overview of biogas utilization

(Abanades S., 2021)

Biogas has many energy utilizations, depending on the nature of the biogas source and the local energy demand. In developing countries it is most commonly used in stoves, lamps and engines. The most efficient way of using biogas is in a heat-power combination where 88% efficiency can be reached (Kossmann et al., undated).

1.4. BOIGAS FOR COOKING

For transporting biogas from the digester to the cooking place a tube is needed. Stoves for this system contain a valve to premix the biogas with the right amount of oxygen, a burner to combust the mixture and a structure to hold a cook-pot. Stoves and ovens for biogas application are similar to those of conventional appliances running on commercial gas-fuels. Most of these conventional appliances can be adapted for the use with biogas by special measures (particularly the modification of the burners) to ensure proper combustion and efficient use of energy.

Figure 9 : Biogas cooker (SPEAKERTHEME, 2020)

1.5. BIOGAS ELECTRICITY

“The fate of people on Earth depends on whether we can employ efficient and renewable energies. We need to lay big plans for small technologies.” — David Freeman, speaking at the World Renewable Energy Congress in June 1996 P 7, (Pahl G, 2012).

Biogas is a promising renewable source of energy. It can be directly converted into electrical power, for example, in a fuel cell. It can be burnt, releasing heat at high temperature. According to the Global Bioenergy Statistics 2018, electricity from biomass (Bio-power) is the 3rd largest renewable electricity source globally after hydropower and wind. In 2016, 571 TWh of bio-power was generated globally – 65 % from solid biomass sources like wood chips and wood pellets, 19% from municipal and industrial waste followed by 15 % from biogas - mainly in Europe. Electricity only plants refer to plants designed to generate electricity only while the heat is not utilized. Combined heat and power (CHP) plants is the simultaneous production and utilization of heat and electricity. The use of cogeneration leads to higher overall efficiencies as the heat is also utilized – predominantly for district heating networks.

1.5.1. Biogas converting generator

Combined heat and power generation

CHP generation is a standard utilization of biogas from AD in many countries with a developed biogas sector, as it is considered a very efficient utilization of biogas for energy production. Before CHP conversion, biogas is drained and dried. In principle, CHP units consist of a combustion engine fueled by biogas, driving a generator used for producing electrical energy. The principle behind CHP units is to recover the waste heat generated by the combustion of a fuel in an electricity generation system. This cogeneration of electricity and heat greatly increases the overall efficiency of the system, anywhere from 25-55 % to 60-90 %, depending on the equipment used and the application. CHPs are very common in biogas plants. The total efficiency, i.e. the sum of the electrical and thermal efficiencies, is within the range 85–90 % with modern CHPs. Only 10–15% of the energy of the biogas is wasted. But the electrical efficiency (maximum 40%) is still very low: from 1 m³ biogas only 2.4 KWh electric current can be produced. A CHP plant based on a gas turbine is shown in Figure 8 below.

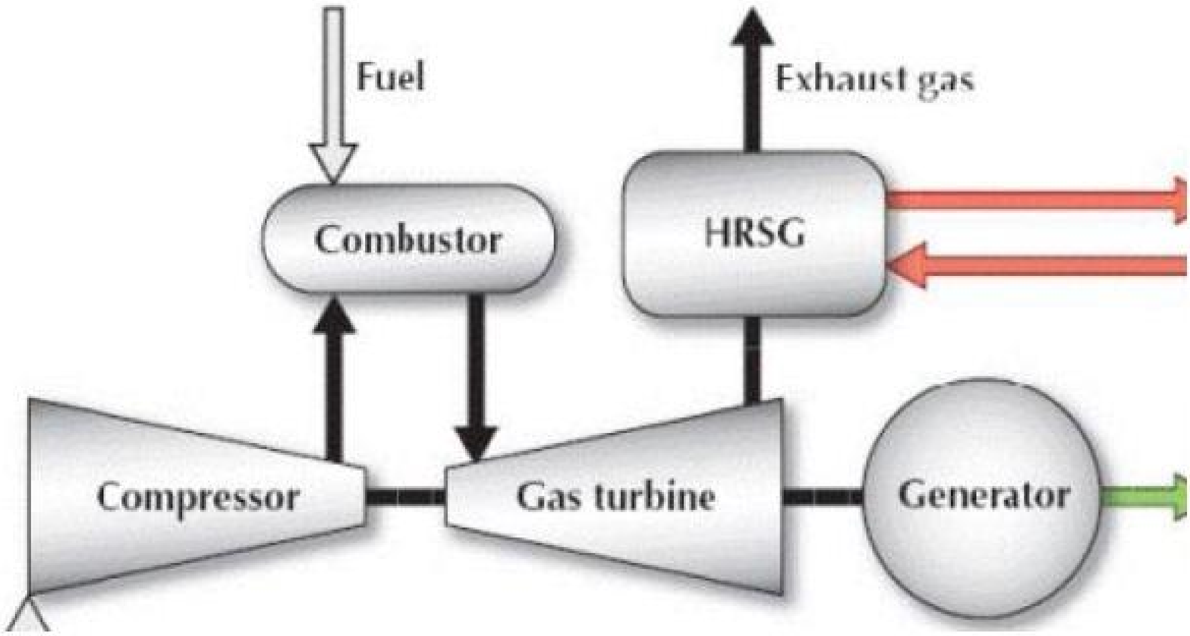

Figure 10: CHP unit of a biogas plant

(Al SAEDI 2001).

1.5.2. Bioenergy in cameroon

In Cameroon, hydropower and fossil fuels are the major sources of electricity supplies with the former being a renewable and the later a non-renewable resource. Both types of energy sources are known for certain environmental problems; for instance the non-renewable energy type creates room for colossal pollution and hydropower on the other hand is known for problems such as: biodiversity loss, interrupted water flows, loss of water via evaporation, barriers to animals, mercury leakages from high tension step- down transformers among others. Furthermore, reliability of hydropower for Cameroonian utilization is not only insufficient but also very expensive to set up such a power plant. Cameroon is ranked the third largest sub Saharan African country when it comes to biomass potential (J.N Mbi no date) Biomass and waste (wood, sawdust and charcoal) are the primary sources of energy supply to

both rural and urban population in this country, constituting over 63.5% of the total sources of energy use as seen below:

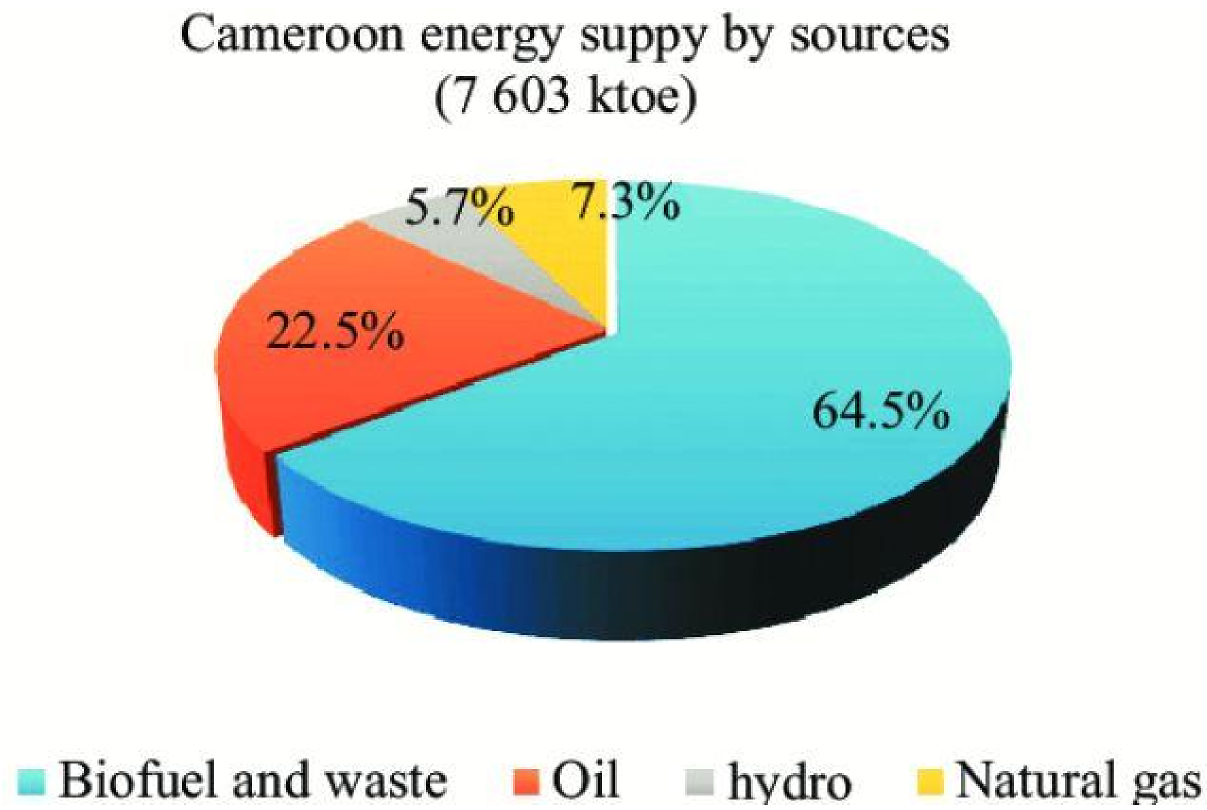

Figure 11: Sources of energy used in Cameroon

(IEA Statistics, 2009)

Biomass energy production in Cameroon is often small scale and more often for home use and exploitation. Among the factors responsible for poor implementation of renewable energy developments in Cameroon are: inadequate renewable energy planning policies; poor infrastructure and institutional framework; inadequate harmonization in renewable energy programmes; very high initial capital cost; meagre baseline information and poor maintenance services among others. These are summarised into four major barriers as follows: policy, financial, technical and social barriers.

- **Policy Barrier**

In Cameroon, the 1990 national energy plan which integrates renewable energies was never entrenched nor revised in spite of the numerous energy crises faced by the country, rather the renewable energy policy laid more emphasis on hydroelectricity to the detriment of solar and biomass resources. Furthermore, the policy placed more emphasis on supplying energy to the urban area thereby neglecting the low income rural population (Encyclopedia of Nations, 2009).

In fact, the government of Cameroon has created a vacuum in the renewable energy sector as there is no clear- cut policy on the operation in this sector thereby allowing no clear link to the already poor national master plan. It is no surprise that Cameroonians have no knowledge of government policy intending to promote renewable energy development (Ngnikam and Tolole, 2009). With the present energy policy of Cameroon, the budget allocated to small and medium scale renewable energy technologies remains very little when compared to that of conventional energy sector and hydroelectricity.

- **Economic Barrier**

Majority of the less privileged Cameroon populations with national poverty levels of 50-70% are unable to afford highly developed renewable energy technologies (World Bank, 2001). Expensive renewable energy technologies with high cost of imported components results in extra load on foreign exchange reserves of the country, which are often very small and approaching collapse, and need expensive financing schemes and huge subsidies (Karekezi and Kithyoma, 2002).

- **Technical Barrier**

In Cameroon the introduction of renewable energy technology is pretty new and unfamiliar concept and this explains why qualified personnels are deficient. The situation of inadequate technical expertise is seen both in the formal and informal sectors, but the later situation presents a greater challenge, as technical skills are mainly mechanical. Hence artisans in the informal sector find it more complicated to grasp electrical technologies to a bulk of end users, particularly in rural areas of the country. To a greater extent, this may be an explanation for the low uptake of electrical renewable energy technologies.

- **Social Cultural Barrier**

Socio–cultural issues and adamant to change especially when it has to do with strange technologies are possible obstacles to bioenergy technologies adoption and dissemination in Cameroon. Even after educating the people on the possible means of reducing energy expenses by means of simple renewable energy technologies, they remain adamant to change. The principal reasons for unyielding to change could be attributed to the fright of discarding the already familiar technologies for the unfamiliar and fear of the possible dangers inherent in the use of RET (especially the case of biogas accident).

Conclusion

Technologies for the exploitation of biogas power are constantly being developed and the energy gap in Cameroon remains one of the greatest obstacles to the country's sustainable development, with an estimated increasing gap of 8% (Tansi, 2011). For this gap to be narrowed, the potentials of renewable especially bioenergy from waste should be fully developed and an institutional framework that warrant continuity for posterity must be taken into consideration.

CHAPTER 2: MATERIALS AND METHODS

Introduction

This chapter presents the general physical and environmental conditions of the study area together with the materials and methods used in this study.

2.1. PRESENTATION OF STUDY ZONE

2.1.1. Location

Geographically, Yaoundé is located between latitude 3 º 45’’ and 4 º north and longitudes 11 º 00 ’’ and 11 º 30 ’’ east.

The department has only 1 urban community, the Yaoundé urban community. The urban community has no elected mayor, but a government delegate. However, each of the 7 current boroughs has an urban district council, elected with an urban district mayor as its head. The urban community covering the entire department makes it a special status community. The department has 7 districts as shown below

- Yaoundé I (Nlongkak), (Etoudi)
- Yaoundé II (Tsinga)
- Yaoundé III (Efoulan)
- Yaoundé IV (Kondengui)
- Yaoundé V (Essos)
- Yaoundé VI (Biyemassi)
- Yaoundé VII (Nkolbisson)

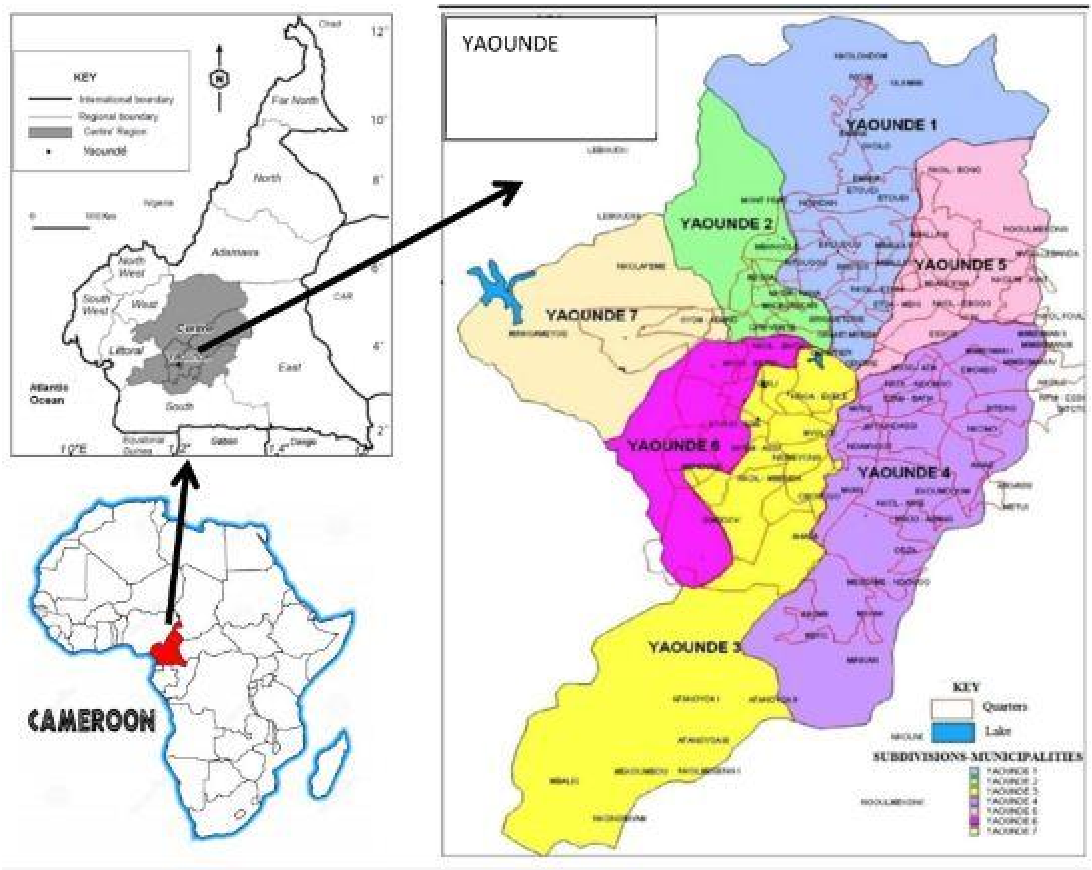

Figure 12: Map of Cameroon showing the position of Yaoundé and its different districts (Système d"Information Géographique», Communauté Urbaine de Yaoundé, Cameroon, 2011)

2.1.2. Physical parameters

1. Climate

The climate of Yaoundé is uniform in all the town, and it is equatorial, type Guinean. It is characterized by two types of wind blowing across the town. The cold and dry Harmattan, blowing from November to March which brings the dry season; and the monsoon (hot and humid) which blows from April to October and brings the rainy season (Ngon-Ngon et al., 2009). The annual average rainfall is 1,643mm and the rainiest month is October with value of precipitations reaching 300 mm while January is the least rainy month. Between the driest and wettest months, the amplitude of precipitation is 276 mm. 2.0 º C of temperature variation is observed throughout the year. The average of 24.6 º C make the month of March the hottest of the year. 22.6 º C make the month of August the coldest of the year. Below is the figure illustrating the climatic conditions in Yaoundé.

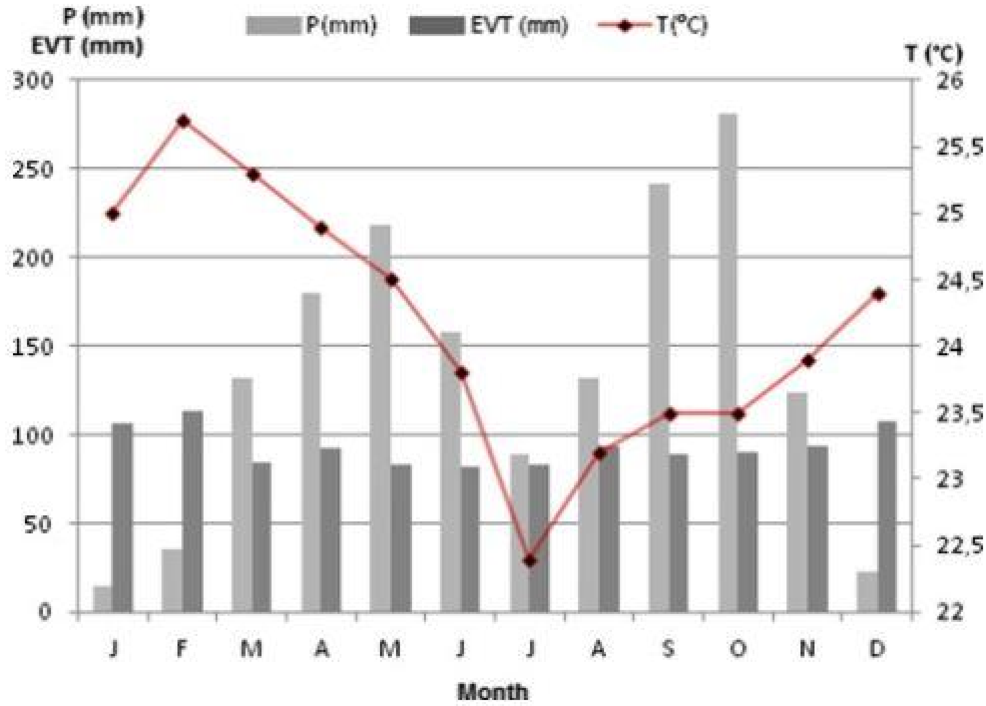

Figure 13: The annual climatic conditions in Yaoundé

(www.ccsenet.org/jgg, 2014)

1 Hydrogeology

Yaoundé has an arborescent hydrographic network with the Mefou and Mfoundi being the main rivers. This hydrographic network has developed flat valleys with different widths ranging from 50 to 150 m (Ngon-Ngon et al., 2009). The geomorphology is influenced by lithology and structure of the underlying formations and plays a pivotal role in the occurrence and distribution of groundwater (see figure 14) Geologically, the Neoproterozoic basement is composed of gneisses and migmatites. Meta sedimentary rocks are the most abundant outcrop along the beds of some rivers (Mvondo et al., 2003; Nzenti, 1998).

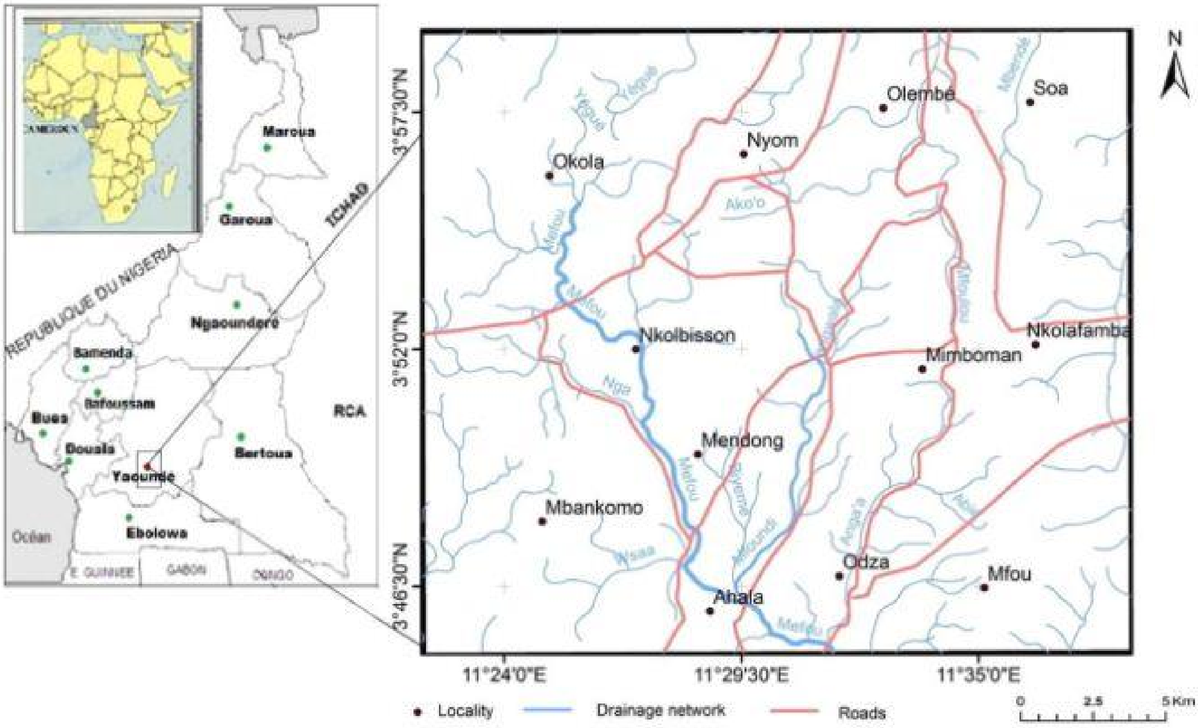

Figure 14: Hydrographic network of Yaoundé

(www.ccsenet.org/jgg, 2014)

2 Demography

According to the United Nations the current population of Yaoundé in 2019 is 3,822,000 which a 4.54% increase from 2018. The table below shows the population and growth rate since 2009.

Table 5: Historical population data of Yaoundé (United Nations- world population prospects

Year	Population	Growth rate
2009	2,222,000	5.66%
2010	2,349,000	5.72%
2011	2,482,000	5.66%
2012	2,623,000	5.68%
2013	2,773,000	5.72%

2014	2,930,000	5.66%
2015	3,097,000	5.70%
2016	3,273,000	5.68%
2017	3,459,000	5.68%
2018	3,656,000	5.70%
2019	3,822,000	4.54%

The population and growth rate projections of Yaoundé up to 2035 are shown in the figure below

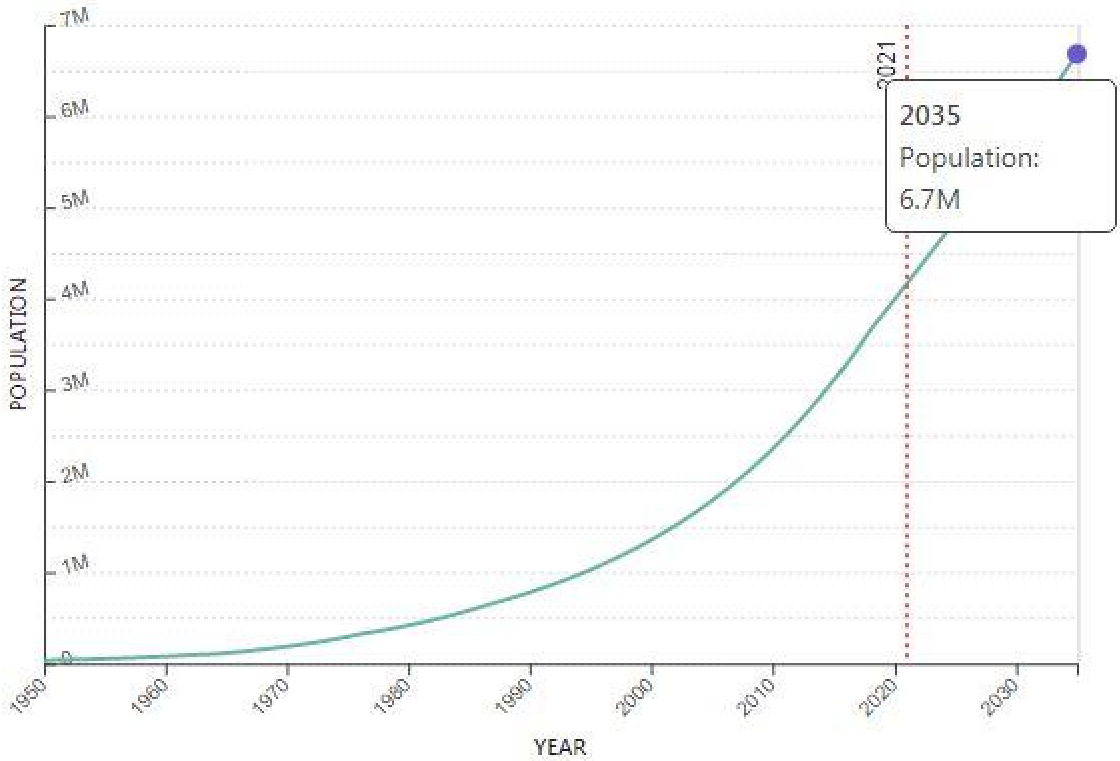

Figure 15: Population projections of Yaoundé

(World Population Review, 2021)

From the graph above, it explains that the population of Yaoundé is expected to increase at a decreasing rate. This also explains that by the year 2035, the population of Yaoundé will stand at possibly 6.7 million persons.

2.1.3. Faecal sludge production in Yaoundé.

Yaoundé is an urban area of approximately 256 km² and is located between about 700–800 m above sea level. The town had an estimated population of 2,4 million inhabitants in 2011(BUCREP, 2012). The City faces overpopulation like many other urban cities in developing countries with a density of 14,000 inhabitants/km². Parrot et al. (2009) mentioned that more than half (51 %) of the capital consists of slums with no pipeborne water supply and no centralized sanitation and waste disposal infrastructure. A good percentage of the population relies mainly on shallow dug wells and springs for drinking water sources (Graf et al., 2010). Yaounde has an equatorial climate with four seasons comprising two dry seasons (December-February, July- August) and two rainy seasons (March-June, September-November). The average annual rainfall is 1,600 mm with an average temperature of 23 °C (Lienou et al., 2008). On-site sanitation systems for excreta collection are widespread with the predominance of pit latrines (> 59%). The city has no FS treatment station up till recently (ongoing construction a etoa-barriere) and it was estimated that about 700 to 1,300 m³ of FS are discharged weekly into the environment of peri-urban areas (Marie M, 2021).

Assessment of the existing faecal sludge management practices at household level

To assess the faecal sludge management practices in households, a heterogeneous stratified sampling method was applied in different urban settlements previously identified in the study area. Therefore, a total of 22 settlements were selectively chosen in the study area according to the heterogeneity of urban settlements of Yaounde and represented by peri-urban interfaces, planned urban area, informal settlements, middle and high income areas according to the methodology described by Lüthi and Parkinson (2011). For these authors, every city is a patchwork of different domains and physical environments, each of which presents their own challenges and opportunities. The size "n" of the households investigated as a function of the total population "N" was estimated using the margin of error formula for defined population (Barlett et al., 2001): With ―N‖ the size of the total population of Yaounde (estimated at about 2.4 million inhabitants (BUCREP, 2012), ―n‖ the sample size, ―e‖ the marginal error set to 5 % in the case of this study. The size of sample obtained using the formula have shown a total of 402 households. To limit errors and to increase the viability of results, the sample size was adjusted to 602 households which were chosen as sampling and analysis unit, while on-site sanitation facilities were organized and managed as property according the sampling methodology described by Jenkins et al. (2014).

2.2. MATERIALS USED

Having full knowledge on the approach used in the course of a research facilitates and the understanding of the kind of conclusions drawn at the end of this research work, this research can be qualified as qualitative and quantitative.

2.2.1. Qualitative research

This kind of research focuses on human perception. It explains how people think as well as how they relate concerning the subject matter. According to Elame (2017), a qualitative research does not seek to quantify or measure but targets in getting verbal expressions which permits us to do an interpretation. this was done through the administering of questionnaires to 60 individuals in different areas in the city (APPENDIX). Questions 1, 2 and 3 concern the ownership of the structure (home or institution), the position held by the person answering the questionnaire and information on the number of persons currently leaving/working in the structure. Questions 4 to 16 concern the type of livestock, quantity, slaughtering processes, waste types, methods of waste collection and water consumption. Questions 17 to 19 concern electricity applications, consumption and source. Lastly question 20 concerns any knowledge of biogas production and willingness to engage in the activity.

The main tool in a qualitative research is an interview which could either be individual interviews or group interviews (also known as Focus groups).

2.2.2. Data collection

Data collection is the process of gathering and measuring information on variables of interest in an established systematic fashion that enables one to answer a stated research question, test hypothesis and evaluate outcomes. The following instruments were used for the collection of data.

1. Camera: used to take snapshots of certain scenes useful for the case of this study.

2. Laptop: This was used for the storage, computations, typing among other functions in the course of the research.

3. Writing material: such as pens, pencils, and note books, were used to collect necessary information and data onsite.

4. Safety attire: like rain boots and a lab jacket put on by the researcher in the very poorly managed zones in the quest to understand the different pipping and treatment methods being carried out.

5. A Calculator.

6. Laboratory apparatus which included; containers, faecal sludge, oven, desiccator, scale balance, furnace.

7. Software used in the realization of this study includes;

- Quantum Geographical Information System (QGIS) for designing of the map of Cameroon and indicating the location of the study site.
- Internet explorer and Mozilla Firefox for research through access to the internet
- Microsoft PowerPoint for project presentation.
- Microsoft Excel for data analysis and representation
- Microsoft Word for typing

2.3. METHODS USED

Data collection for this research work was acquired and assembled from primary and secondary data sources.

2.3.1. Interviews

These interviews were carried out with administrative personnel and various house owners to better understand the general functioning and sludge production capacities, views on waste management and measures being taken as to ameliorating the present conditions.

2.3.2. Observations

This being a voluntary step for the collection for information on the non-verbal behaviors relating to the subject matter and consists of 3 types. That is, systematic, participative and free observation (Elame, 2017). For this research, the systematic observation was used in which the researcher does not participate and made use of an observation guide.

2.3.3. Questionnaire

For the purpose of doing statistical measurements was formulated with a total of twenty (20) questions which could be an aid towards the researcher to validate or invalidate the research hypothesis, in the research zone of Yaoundé. These questions serve as a tool in validating or invalidating the research hypothesis as well as gives a grasp on the reasoning of the population sampled and also enabled them to do an evaluation for themselves on their waste management. During the period of this work, a total of 40 questionnaires were distributed in over 30 places (homes and institutions) in the city of Yaoundé (Appendix). Questions 1, 2 and 3 concern the ownership of the structure, the position held by the person answering the questionnaire and information on the number of persons currently leaving or working in the structure. Questions 4 to 16 concern the waste types, methods of waste collection and water consumption. Questions 17 to 19 concern energy consumption and source. Lastly question 20 concerns any knowledge of biogas production and willingness to engage in the activity.

2.3.4. Analysis of waste samples

In the course of this work, some samples of faecal sludge were collected and taken to the National Laboratory for the Diagnostic Analysis of Agricultural products and Inputs to quantify the percentage of dry matter and organic matter of the waste fractions. These samples included faecal sludge samples from 3 different septic tanks; a fairly used, a semi filled and a pit latrine. This was done to evaluate the potential of the waste for anaerobic digestion. Also, the carbon and nitrogen contents of the different samples were determined in the lab.

Determination of dry matter content

The equipment used to collect FS from the tanks was a 2 litres stainless steel container attached to a 3 m rod. The samples are then collected into 1 L bottles which are carried to the lab immediately for sampling.

However, this type of sampling device is difficult to use with thicker sludge or sludge with large amounts of solid waste, because it is difficult to push the device through the layers taking a core sample from a septic tank . As seen, the sampling device becomes clogged if the sludge is too thick. This example shows the collection from a 10-year old septic tank that had never been emptied resulting in a very thick sludge accumulation.

Figure 17 : FS collection

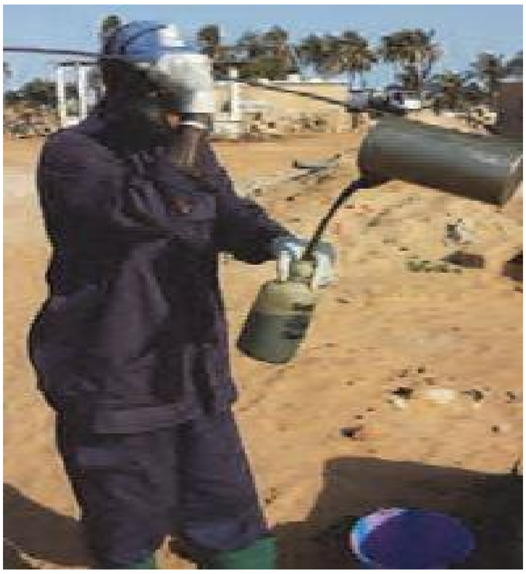

Figure 16 : FS collection into 1L

Figure 18 : Containment flask

The dry masses percentage of each of the bottled content were then calculated using the formula below

Initial mass before drying = M_I

Final mass after drying = M_F

Dry mass, DM = $\frac{M_F}{M_I} \times 100\%$

Determining the volatile matter biodegradable fraction of the waste

Organic Matter, OM = $\frac{M_I - M_f}{M_I} \times 100\%$

Where M_I is the mass before placing in the furnace and M_F is the mass after removal from the furnace

2.3.5. Evaluating the potential for cooking gas production from faecal sludge in Yaoundé

This section evaluates the potential quantity of biogas that can be produced from faecal waste and its subsequent use for cooking.

A. Choice of technology

Aerobic treatment is currently the most common process used to reduce the organic pollution level of both domestic and industrial wastewaters. Aerobic techniques, such as trickling filters and oxidation ponds with more or less intense mixing devices, are applied for domestic wastewater treatment in many small communities. Activated sludge processes were introduced for larger communities and industrial wastewaters. Recent developments have, however, revealed that anaerobic processes may be an economically attractive alternative for the treatment of different types of industrial wastewaters and, in (semi-)tropical areas, also of domestic wastewater. Anaerobic digestion has been rediscovered in the last two decades, mainly as a result of the energy crisis. Major developments have been made with regard to anaerobic metabolism, physiological interactions among different microbial species, effects of toxic compounds, biomass, and biomass accumulation. Anaerobic digestion has revealed a number of benefits over aerobic purification. An obvious advantage of anaerobic digestion is the production of biofuel (methane) from organic waste. Moreover, the anaerobic processes do not require aeration, have a low nutrient requirement and produce only little excess microbial biomass.

Table 6: Characteristics of anaerobic versus aerobic digestion

	Aerobic	Anaerobic
Application example	Trickling filters, oxidation ponds	Anaerobic reactor
Carbon balance	50% - CO_2 50% - Biomass	95% - CH_4+CO_2 (Biogas) 5% - Biomass

Energy balance	40% - Heat production 60% - Biomass	5% - Heat production 5% - Biomass 90%- Retained in CH_4
Biomass production	Fast	Slow

The appropriate method used here will be anaerobic digestion from them above explanation which clearly shows the advantages of the method.

Fixed digester is the anaerobic digester that will be used. The fixed dome digester is a semi batch reactor composed of a fermentation chamber for anaerobic digestion, feed and digestate pipes, and a fixed dome on the top for biogas storage. The reaction and biogas storage chambers are connected. The dome is built mainly with gravel, sharp sand, iron rods and cement. Some of the important design consideration includes local climate, amount of waste and water available to input into the anaerobic digester daily. The lower part of the digester contains a layer of biosolids and a layer of liquid above the biosolids. As the anaerobic microbial processes take place, volatile solids are.

B. Design of biogas plant

The design and calculate the scale of a biogas plant, certain characteristic parameters are used. These are:

- **Evaluation of the biodegradable fraction of waste collected**

This is done by chemical analysis. Biodegradable content is the **total amount of waste.**

That is the volatile matter and its value was gotten from the experiments shown earlier.

- **Organic loading rate**

Organic loading rate (Q) expressed in terms of mass is the proportion of fermentable organic matter in the substrate. It is given as

Q = DM × OM (kg/day).

OM is the percentage of biodegradable organic matter and DM is the dry matter content in the waste.

- **Total solid (TS) contains calculations of organic materials :** Total solid contained in a certain amount of materials is usually used as the material unit to indicate the biogas- producing rate of the materials. Most favourable TS value desired is **08%.**
- **Daily fermentation slurry feeding (Sd)**: This is an equal mixture of biogas feedstock (animal dung, human feces, poultry waste and jatropha byproduct) with water feed into the biogas digester.
- **Retention time (RT)** which is the time by which the fermentation slurry stays in the digester. It is about 3–5 weeks.
- **Digester loading (R).** This parameter indicates the amount of biogas feedstock material per day is fed to the digester or to be digested. It can be measured in $kg/m^3/day$.
- **Specific gas production per day (Gd),** which depends on the retention time, the digestion temperature and the feed material.

<u>Sizing of biogas digester and gasholder</u>

The size of the digester—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 considered in this study (e.g., cattle dung) and the mixing water.

1. **Sizing of site-A biogas digester and gasholder**

Evaluation of the daily production of biogas

P = Mass of organic fermentable matter × B_0 (m^3/day)

P = the average daily production of biogas,

Bo = average specific biogas for a given substrate.

Average biogas productivity considering the DRANCO technology is taken as $0.14 m^3/kg$ for a retention time of 20 days. In this case we will consider Bo as $0.15\ m^3/kg$ in 25days. According to Amarante 2012, production drops enormously after 20days so the rate of production is reduced from $0.07\ m^3/kg$ to less than $0.04 m^3/kg$.

2. **Evaluation of the daily production of methane**

The daily production of methane was obtained from the relation below

Qm = P × x (m^3)

Qm = daily production of methane

x = proportion of methane produced in the substrate. In this work, x will be considered as 60% according to table 3 on chapter 1(AL SEADI 2001)

3. **Daily production relative to LPG**

1kg of LPG = 2 litres of LPG = $2m^3$ (2000litres) of methane (energypedia.com)

$1m^3$ of methane = 0.5kg of LPG

1litre of methane = 0.0005kg of LPG

4. **Sizing the substrate storage-pit or pre storage pit**

This is a first tank for storing the substrate that has to be processed to biogas. Its volume is not necessarily important because the stored materials are not staying long time. Access to this tank should be easy for the introduction and withdrawal of products without great difficulty.

Volume of storage pit = 2 × Volume of the substrate (m^3)

5. **Calculation of biogas reactor volume and sizing the digester**

Figure 19: Shape of the digester

Total volume (Vt) = retention time for the substrate x volume of the substrate loaded per day (m^3)

Also,

Total volume = volume of the cylindrical portion (Vcylinder) + volume of the conical portion (Vcone)

To facilitate digester calculations,

Let Hint = Rint and Hint = 2hint

Where Hint = internal height of the cylindrical part of the digester,

hint = internal height of the conical part of the digester and

Rint = internal radius of the cylindrical and conical parts of the digester.

Because most of the piston pumps encountered on the market do not pump more than 20 m in height, the external height of the digester plus 10% must not exceed 17 m. The increase of 10 % corresponds to all the losses.

The volume of the cylinder is given by

$\boldsymbol{V_{cylinder}} = \pi R_{int}^2 H_{int}$ And if $H_{int} = R_{int}$

Then $\boldsymbol{V_{cylinder} = \pi R_{int}^3}$

The volume of the conical part of the cylinder is given by:

$\boldsymbol{V_{cone}} = \pi R_{int}^2 h_{int}/3$ or $H_{int} = 2h_{int}$.

Then $\boldsymbol{V_{cone}} = \pi R_{int}^2 h_{int}/6 = \pi R_{int}^3/6 = \boldsymbol{V_{cylinder}/6}$

This implies $\mathbf{V_{cylinder}} = \mathbf{6\, V_{cone}}$

The total volume of the digester is given by

$$\boldsymbol{V_t = V_{cylinder} + V_{cone} = 7\, V_{cone} = \frac{7}{6} \pi R_{int}^3} \text{ (m}^3\text{)}$$

Where $\boldsymbol{R_{int} = \sqrt[3]{\frac{6\, x\, V_t}{7\, x\, \pi}}}$ **(m)**

This is the radius of the cylinder base and the base of the digester of the cone.

Total internal height of the digester will be given by

$\boldsymbol{H_{total\ internal} = H_{int} + h_{int}}$ **(m)**

6. Sizing the storage pit or tank

This pit used to store methanized substrates, and sometimes part of the BIOGAS produced in the digester. It is important to note that depending on the digestion time a volume of "residual" BIOGAS can be produced in this tank during the storage phase. It is therefore important this pit should be firmly covered to avoid leakage of methane and CO_2 to the environment.

This tank may be connected to the gas holder to optimize the recovery of biogas. The volume of the storage tank depends on the frequency of application which in this case will be taken as 30 days. The volume of the storage tank is then given by the formula:

Volume of the storage pit or tank = 30 × volume of the substrate available daily (m³)

7. Volume of the gasometer

The volume of the gas holder (Vg) depends on the relative levels of production and consumption of biogas. Consider a gasometer that can store gas produced in 5 hours. This is given by

V_g = 5 x Hourly production rate of biogas (m^3)

8. Evaluation of the thermal energy in the digester

Considering that the tank is underground, it must be more or less thermally insulated in order to avoid heat losses and/or to offer contact protection when the reactor is run in a thermophilic process. As insulating material, expanded plastic slabs of polyurethane are used within the lower zone of the wall. They are equipped with moisture barriers in order to prevent the penetration of water. In the upper zone of the tank wall, expanded polystyrene slabs are often installed, or alternatively plastic foam is attached. The thermal insulation is covered with riveted metal sheets

Figure 20: Insulation of the digester

The characteristics of these material layers enable the calculation of thermal losses by diffusion.

Neglecting convection losses, knowing thermal conductivities of steel λ_s and polystyrene λ_p with thickness e_s and e_p respectively, the thermal resistances can be written down as follows

For steel :

$$R_{\text{thermal resistance of steel on lateral side}} = R_{sl} = \frac{\ln\left(\frac{R_{int} + e_s}{R_{int}}\right)}{2\lambda_s \pi H_{ms}}$$

$$\mathbf{R_{thermal\ resistance\ on\ dome\ side}} = \mathbf{R_{sd}} = \frac{e_s}{\lambda_s \pi R_{ms}^2}$$

For polystyrene,

$$\mathbf{R_{thermal\ resistance\ of\ polystyrene\ on\ lateral\ side}} = \mathbf{R_{pl}} = \frac{\ln\left(\frac{R_{int} + e_s + e_p}{R_{int} + e_s}\right)}{2\lambda_p \pi H_{mp}}$$

$$\mathbf{R_{thermal\ resistance\ on\ dome\ side}} = \mathbf{R_{pd}} = \frac{e_p}{\lambda_p \pi R_{mp}^2}$$

Where

$H_{ms} = \frac{2H_{int} + e_s}{2}$ is the average height of the steel

$H_{mp} = \frac{2(H_{int} + e_s) + e_p}{2}$ is the average height of the polystyrene

$R_{ms} = \frac{2R_{int} + e_s}{2}$ is the average radius of steel on the dome part of the digester

$R_{mp} = \frac{2(R_{int} + e_s) + e_p}{2}$ is the average radius of polystyrene on the dome part of the digester

H_{int} is the internal height of the cylindrical part of the digester

R_{int} is the internal radius of the base of the cylinder of the digester

Conical part

$$\mathbf{R_{thermal\ resistance\ of\ steel\ on\ conical\ part}} = \mathbf{R_{sc}} = \frac{e_s}{2\lambda_s \pi R_{ms} G_{ms}}$$

$$\mathbf{R_{thermal\ resistance\ of\ polystyrene\ on\ conical\ part}} = \mathbf{R_{pc}} = \frac{e_p}{2\lambda_p \pi R_{mp} G_{mp}}$$

Where $G_{ms} = \sqrt{2R_{ms}}$ is the heat generating factor of steel in the conical part

$G_{mp} = \sqrt{2R_{mp}}$ is the heat generating factor of polystyrene in the conical part.

The thermal resistance on each side is therefore given by

Lateral side: $\mathbf{R_{sl}} + R_{pl}$

Upper side: $\mathbf{R_{su}} + \mathbf{R_{pu}}$

Conical side: $\mathbf{R_{sc}} + R_{pc}$

The total thermal resistance of all three sides being in parallel

$$\mathbf{R_{total}} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\mathbf{R_{sl}} + \boldsymbol{R_{pl}}} + \frac{\mathbf{1}}{\mathbf{R_{su}} + \mathbf{R_{pu}}} + \frac{\mathbf{1}}{\mathbf{R_{sc}} + \boldsymbol{R_{pc}}}}$$

Knowing the temperatures of the interior and exterior of the digester the heat loss can be calculated as

$$\textbf{Heat loss} = \frac{T_{digestion} - T_{exterior}}{R_{total}}\ \textbf{(W)}\ \text{and}$$

Total energy loss = Heat loss × 24 (Wh/day)

2.3.6. Treatment of biogas

Before admission of the gas into the electrical motor, the gas has to undergo treatment with respect to the usage. In the present case where the gas will be used for electricity, required treatment will be drying and compression of the gas as there exist different motors that function with corrosive biogas. The method of treatment will be with respect to the rate of production of the gas.

This work is done only for the purpose of using the biogas as cooking gas.

2.3.7. Data analysis

Hence, data collected was analyzed with the use of Microsoft Excel Spreadsheets and thereafter, the results were represented using graphs, tables and charts. Similarly, data collected from interviews were analyzed but with general points that were collected and related to works already done in order to pull out conclusions concerning them.

1) ECONOMIC ANALYSIS

The economic analysis of the project took into account the cost of investment into the project

- **Cost of investment of the project**

Investment cost takes into account,

- Site layout, digester, post digester storage

- Reception of materials and hygienization

- Digestate management

- Biogas recovery

Having a biodigester installed and receiving training to use and maintain it costs 500,000-700,000 FCFA ($893-$1,250), a sum paid by the institution or households that request the service. A group of homes can use a common biodigester to share the expense. Especially since it has a life span of 15years (Ngalame E., 2016). Average value can be taken at $1,071.

Cost of investment (FCFA) = $1,071 × 560 + cost of operation and maintenance.

= 600,000 FCFA

- **The cooking gas purchase frequency**

This will be taking into consideration the cost saved by the household in buying energy from the local vendors of LPG in Yaoundé and the cost of the sale of compost to the local markets.

The cost saved for energy consumption will be calculated as a function of the price fixed by local vendors per bottle of LPG.

- Cost of energy saved (FCFA) = Cost of 1 bottle of LPG × number of refills per year
- **= 6500 x number of refills per year.**

An average family of 5-7 people could use a bottle of gas for averagely a month implying 12 refills a year. Thus, cost of energy saved = **78000FCFA**

The quantity of digestate obtained at the end of the anaerobic digestion is equal to 35% of the amount of substrate introduced into the digester. Therefore if the digestate is sold at a rate of 1000FCFA per 100kg, or 10FCFA per kg, we will have

- **Cost of sale of compost (FCFA) = 10 × 365 × daily substrate input × 35/100**

The present value for cash flows is given as

$$V_p = \sum_{k=1}^{N} \frac{\mathrm{CF_K}}{(1+\mathrm{r})^{\mathrm{k}}}$$

The net present value NPV which is the net present value of a future gain will be calculated as;

$$\mathbf{NPV} = -I_0 + V_p$$

The profitability index is given by

$$P_1 = 1 + \frac{NPV}{I_0}$$

Where **PI > 1, the project will generate value**

PI < 1, the project destroys value

Where I_0 is the initial investment, $\mathrm{CF_K}$ is the cash flow generated over the year, **N** is the life of the project, **r** is the discount rate.

Conclusion

Through this chapter, the researcher presented the environmental and human conditions of the city of Yaoundé together with the current state and conditions of FSM in the city. The materials used and methods through which this study was able to be achieved have also been stated in the chapter.

Chapter 3: RESULTS AND DISCUSSION

INTRODUCTION

Having presented the study zone, research methodology and the state of sludge management in Yaoundé, it is necessary for the researcher to present verifiable statistical data on the present state of the municipality which will enhance the work on proposals. These proposals are of utmost importance in this work. This chapter is focused on averaging the settlement, estimating possible methane potential generated from the organic waste in the sludge containment tanks of an average household in Yaoundé and expected costs for the construction of a bio-digester for biogas consumption (cooking gas).

The potential of biogas from faecal sludge amounts to 0.009 to 0.028 m³/kg VS which can be most comfortable if used as cooking gas in households with small scale biogas plants .

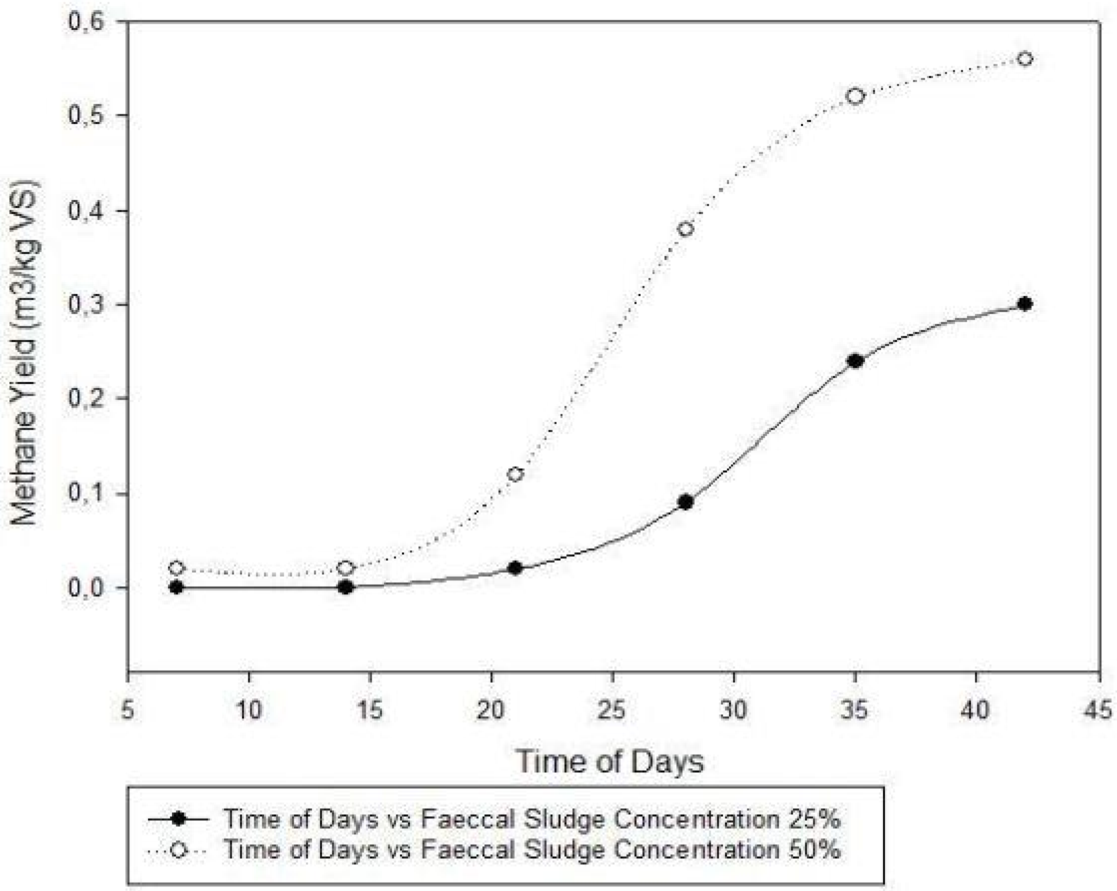

Figure 21: Methane Yield Cumulative Graph during Operational Reactor

(Ukhtiy A, 2019)

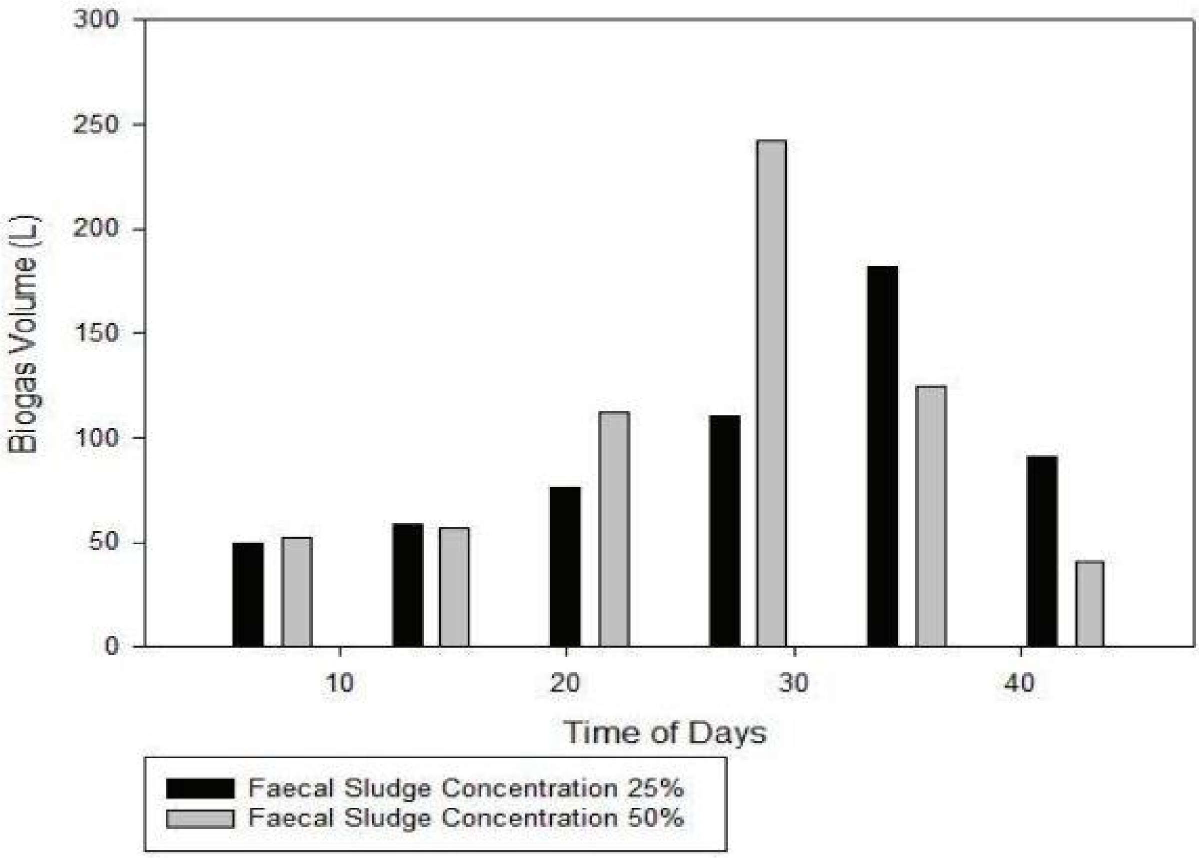

Figure 22: Biogas Volume Graph during Operational Reactor

(Ukhtiy A, 2019)

Graph showing that HRT is between 20 and 40 days after which the rate of biogas yield drops drastically. This is the reason why this work could not show for anything substantial as per encouraging a large scale yield of biogas if it was the sludge from the emptying of septic tanks all around the city that had to be valorized for biogas production. Especially seeing as septic tanks only fill up after 7-10years of use.

3.1. RESULTS

3.1.1. Stakes of biogas production

After a few days of decomposition, the capturing of biogas can begin. This avoids the emission of methane generated by the garbage into the atmosphere, which is harmful to health and the environment. A biogas plant has a life span of at least 15 years.

Reducing pollution is a genuine concern for some Cameroon’s civil protection agents who work to ensure that pollution does not become a danger to the population (Africanews, 2017).

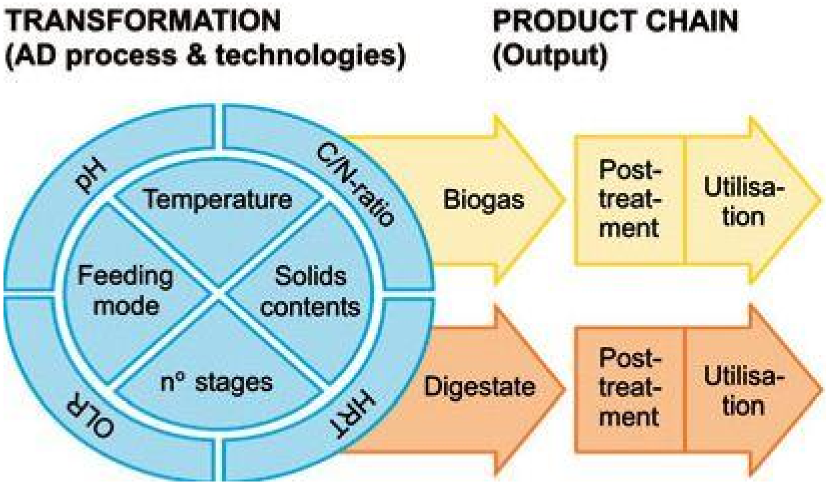

Figure 23: Summary of biogas production

Table 7 : AD contribution to SGDs

Sustainable development goal	**Contribution of AD**
Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture	Restoring soils through the recycling of nutrients, organic matter, and carbon Increasing crop yields through use of nutrient-rich digestate bio-fertilizer
	Recirculating phosphorus, which is essential for the growth of plants but limited in supply
Goal 3: Ensure healthy lives and promote well-being for all at all ages	Reducing indoor air pollution by substituting solid biomass-based domestic fuels with biogas
	Treating and recycling sewage and organic wastes to reduce odours and the spread of diseases
Goal 5: Achieve gender equality and empower all women and girls	Reducing the burden of collecting firewood to improve the quality of women's and children's lives, reducing household labour in cooking
Goal 6: Ensure availability and sustainable management of water and sanitation for all	Providing decentralized, local treatment of bio-solids in remote and rural communities to reduce odours and the spread of disease
	Stabilizing and recycling bio-solids through AD to allow them to be applied back to land

	Reducing the carbon loading of wastewater to reduce impact on water bodies.
Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all	Reducing dependence on fossil-fuel-based energy sources by replacing with biogas
	Capturing waste heat from co-generating units linked to biogas plants
	Utilizing locally produced wastes and crops to generate energy for rural and remote communities
	Storing biogas to produce energy when required
Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	Improving the self-sufficiency and sustainability of industries by extracting the energy from their own effluents and using it for the self-generation of electricity and/or heat
	Collaboration between industries and agriculture for mutual benefit
	Generating short-term construction employment and long-term equipment manufacturing and maintenance employment
	Encouraging growth of micro-enterprises by providing reliable electricity that can be stored and used when needed, that is baseload energy
Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable	Preventing spread of diseases through collection and proper management of organic waste

	Improving sanitation and hygiene through decentralized and local treatment of bio-solids
	Stabilizing the sludge from wastewater treatment to protect the marine environment and urban air quality
	Improving urban air quality by substituting fossil fuel with bio-methane in vehicles
	Improving urban air quality by substituting solid fuel for domestic cooking and heating with biogas
	Reducing greenhouse gas emissions by using biogas-based renewable energy in buildings, homes and industry
	Reducing carbon dioxide emissions by replacing fossil-fuel-based energy sources with biogas and commercial fertilizers with digestate bio-fertilizer
Goal 13: take urgent action to combat climate change and its impacts	Reduction of methane and nitrous oxide emissions from livestock manures
	Reduction of methane and generation of renewable energy from food and other organic wastes
	Capturing emissions from landfills
	Reducing deforestation by replacing solid-biomass-based domestic fuels with biogas

Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	Recirculating nutrients and organic matter in organic wastes through AD and returning them to the soil in the form of digestate bio-fertilizer
	Substituting firewood with biogas as a domestic fuel, reducing deforestation

Production at HYSACAM

This is Cameroon's hygiene and garbage company "HYSACAM", and is determined to combat pollution in Yaoundé. Each day, the centre processes nearly 1300 tons of garbage collected by HYSACAM trucks in Yaoundé.

Figure 24: HYSACAM Biogas plant, Yaoundé.

Production of biogas remains indeed in its infancy in Cameroon. Only HYSACAM, a company managing refuse collection contracts in the country, currently invests in biogas production initiatives thanks to the construction, in Douala and Yaoundé, of two catchment plants set near its landfill sites.

Advantages of Biogas

1. **Renewable Source of Energy, Eco-friendly and greatly reducing pollution issues**

Biogas is a renewable, as well as a clean, source of energy. Gas generated through biodigestion is a renewable, as well as a clean, source of energy. Gas generated through biodigestion is non-polluting; it actually reduces greenhouse emissions (i.e. reduces the greenhouse effect). No combustion takes place in the process, meaning there is zero emission of greenhouse gasses into the atmosphere; therefore, using gas from waste as a form of energy is a great way to combat global warming. Methane that is 27 times more polluting than CO_2, which in a normal way which could have been released is trapped and converted into energy.

Unsurprisingly, concern for the environment is a major reason why the use of biogas has become more widespread. Biogas plants significantly curb the greenhouse effect: the plants lower methane emissions by capturing this harmful gas and using it as fuel. Biogas generation helps cut reliance on the use of fossil fuels, such as oil and coal.

Another biogas advantage is that unlike other types of renewable energies, the process to create the gas is natural, not requiring energy for the generation process. In addition, the raw materials used in the production of biogas are renewable, as trees and crops will continue to grow. Human excrements, food scraps, and crop residue are raw materials that will always be available, which makes it a highly sustainable option.

Using the digestate in farms can help protect the local water resources by reducing nutrient run-off and destroying pathogens.

It also lessens the damaging impact and improper waste management.

2. **Utilization of Waste and conserving agricultural land**

Instead of letting the wastes rot in landfills, it is more advantageous to utilize and turn them into biogas. An environmental hazard is reduced due to lesser methane, carbon dioxide, and other greenhouse gases produced. Wastes are turned into energy to utilize for electricity, heating, cooking, and as fertilizers.

Healthy soil and water is important to farmers, their families and the community. The vast majority of farms in Yaoundé are family-owned and active conservation practices can continue to greatly sustain these numerous families if not pass this legacy from one generation to the next.

Implementing manure digesters on livestock facilities can improve soil health by converting the nutrients in manure to a more accessible form for plants to use.

3. Produces a Circular Economy.

The technology used to produce biogas is quite cheap. It is easy to set up and needs little investment when used on a small scale. Small biodigesters can be used right at home, utilizing kitchen waste and animal manure. A household system pays for itself after a while and the materials used for generation are absolutely free. The gas produced can be used directly for cooking and generation of electricity. This is what allows the cost of biogas production to be relatively low.

In large plants, biogas can also be compressed to achieve the quality of natural gas and utilized to power automobiles. Building such plants requires relatively low capital investment and creates green jobs.

Animal manure, food wastes, wastewater, and crop residue are wastes produced by humans and animals. These wastes can cause harm if not process correctly. By turning these organic wastes into biogas, the wastes are converted into a more helpful way. The wastes are made into biogas for electricity, cooking, and digestate as fertilizers.

4. Sustainable Food Production from the use of digestate

A safe, nutritious, and affordable food supply is needed to sustain the constantly increasing populations of Yaoundé. Farmers work hard to meet the growing food demand and remain viable in today’s global marketplace. Efficiently using water and nutrients for crop and animal needs can cut costs, reduce environmental impacts, and contribute to a safer, more productive farm.

Manure digesters on livestock farms can:

- Protect animal and human health by reducing pathogens.
- Convert nutrients in manure into a form that is more accessible for plants to use compared to raw manure. This can increase crop productivity and yield.
- Recycle nutrients on the farm, creating an economically and environmentally sustainable food production system.
- Accept food waste from places like restaurants and grocery stores. This means less food waste is sent to landfills. Food waste has the added benefit of increasing the efficiency of digesters.

5. A Good Alternative for Electricity and Cooking.

Some areas have limited access to electricity and use different biomass for cooking, hampering their way of living. Biogas can provide them a good alternative as it is economical to set up and possible both for small and large scale production. This therefore goes to say that biogas production brings energy independence.

Cameroon is blessed with a vast potential of energy resources. However, their level of valorization is deplorable causing acute energy challenges. Consequently, most Cameroonians, mainly rural dwellers are dependent on traditional biomass and petroleum products for their basic energy needs despite their associated adverse health and the environmental impacts. Thus, there is a need for alternative, affordable and reliable energy sources to meet this energy gap. This study, therefore, reviews and assesses the prospects and sustainability of biogas production in Cameroon. To achieve this, a brief overview of the energy scenarios in Cameroon, the fundamentals of biogas production, and an assessment of the biogas resource potential of the country is carried out. Crop residues were found to be the most valuable biogas substrates in the country with an annual production capacity of $415.57 \times 10^6 m^3$ compared to $10.52 \times 10^6 m^3$ capacity from animal manure. This study also shows a promising future for biogas production in Cameroon given its vast and omnipresent agricultural feedstocks. However, the proliferation of this technology in the country is hindered by the lack of appropriate institutions, policies, regulations, incentives, political will and engagements, technicians and appropriate funding mechanisms. The promotion of biogas production in Cameroon is currently done by local and international NGOs with limited state engagements.

Disadvantages of Biogas

1. Few Technological Advancements

The biogas industry is not yet advanced. Additional research is needed to develop new technology and make production efficient. Also, governments provide more support on established energy sources such as solar, geothermal, wind, and hydropower.

2. Weather Dependence

Like other intermittent energy sources (solar, wind), biogas production is also affected by the weather. Anaerobic digestion happens in an environment with a temperature of 37°C. Heat energy is required in cold climates to produce biogas continually.

3. Contains Impurities

After refinement and compression, biogas still contains impurities. If the generated bio-fuel was used to power automobiles it could corrode the metal parts of the engine. This corrosion would lead to increased maintenance costs. The gaseous mix is much more suitable for kitchen stoves, water boilers, and lamps.

Traditional toilets and storage tanks

In the domain of sanitation, no specific competence has been transferred to the regions by the Law No. 2004/019of 22 July 2004 fixing the rules applicable to the regions. However, these public organizations could have a word to say as far as the prevention, hygiene and the protection of nature are concerned. Unfortunately, the regions understood to have autonomous and organized institutions are still awaited more than 20 years after their creation by the Cameroonian constitution of January 1996 to fulfill their mandates. To sum up, because of many weaknesses observed in the regulation of the sanitation chain, it is easy to question the credibility and consistency of the related institutional framework. Laws and regulations supposed to govern the domain of sanitation and positively change behaviors are not effectively enforced. This lack of credibility and consistency of the institutional framework results in a poor technical management of solid and liquid waste in the city of Yaoundé.

Table 8: Indicators for classifying on-site sanitation systems in Yaoundé (Wilfried A. et al 2019).

System aspect	Indicator description	Indicator type	Definition and measurement applied in this study
Facility design	1- Pit with slab or better	I, SS	Above-ground technology is basic pit with slab; build with concrete, brick, rock or other hard material.

	2- Waste contained in pit	I, SS	Technology has waste pit, septic tank, or concrete to sewer with no exterior waste drain pipe observed by enumerator (assumed if unable to observe)
	3- Below ground pit/tank lined	SS	Below ground technology is part or fully lined, septic tank, or is connected to sewer, to allow for safe waste emptying, and protect shallow groundwater
Waste management (emptying, transport, disposal)	4- Hygienic emptying service locally available	SS	Vacuum tanker service to extract pit waste in sealed tanks and dispose into municipal treatment systems reported as locally available, or user intends to use service to empty in near future
	5- Plot accessible to hygienic emptying service vehicles	SS	Enumerator observation of device physical accessibility (Car, tanker or tug) or actual use of tanker/tug to empty within last 03 years

Functional condition	6- Structurally safe to use	F	Enumerator observation that slab/floor is not collapsing into pit nor in state prohibiting safe use (assumed if unable to observe and not reported)
	7- Not completely full of waste	F	Enumerator observation of pit fullness by measuring depth from slab/top to surface of sludge (assumed if unable to observe and not reported)
	8- Facility has half height walls and half height door or more	F	Enumerator observation of toilette facility superstructure walls, roof, door and height
	8A- (high standard) Facility has roof, full height walls and door	F	Enumerator observation of toilette facility superstructure walls, roof, door and height

Definition: hygienically safe and sustainable (SS), and functioning (F)

Figure 22: Water Closet System **Figure 23: Open PVC pipe into stream**

3.1.2. SWOT analysis

SWOT analysis represents combination of four different factors; S = Strengths of the site which include all factors of production on the site that can be taken advantage of in the project, W = Weaknesses are specific factors in the project which are a hindrance an can be improved on, O = Opportunities include the internal and external factors that be used included in the project to make it effective and T = Threats are the factors that try to inhibit the project. The SWOT analysis of the project goes thus.

Strengths:

- Renewable Energy
- Biogas plants prevent deforestation.
- Solves Organic Waste disposal problem
- Kills harmful pathogens

Dumping of the organic waste in the streets or dump yards leads to the spread of disease causing organisms like Salmonella sp, E. Coli & Shigella sp which causes diseases like Typhoid Fever, Diarrhea, Shigellosis and other air born diseases. The above mentioned pathogens are killed by the fermentation process (Anaerobic Digestion of the organic waste by Methanogenic microbes in the absence of oxygen) in the Biogas plant because most of the diseases causing pathogens are Aerobic in nature.

➢ The manure obtained from biogas plant has higher nutritive value as compared to that of ordinary farmyard manure.

➢ Reduces Global warming & Carbon Foot Print

Mismanagement of waste causes emission of CH_4, N_2O & CO_2 which are the major greenhouse gases that cause global warming. Among those, CH_4 is the third most important greenhouse gas after N_2O and carbon dioxide (CO_2) and has a Global Warming Potential (GWP) 25 times that of CO_2 & N_2O which has the GWP 310 times that of CO_2. In Biogas plant, the greenhouse gases generated (mainly CH_4) is used for cooking/power generation thereby reducing global warming.

➢ Generates Gas used for Cooking, lighting & Electricity generation

➢ No foul smell

➢ One time investment

➢ Safer than LPG

➢ Little or no Maintenance

Weakness:

➢Biogas generated will be in atmospheric pressure

The above mentioned demerit can be overcome either by placing a counter weight or by using pressure boosters based on the capacity of the biogas plant in order to reach the target pressure.

Opportunities:-

➢50 to 100% of LPG replacement

➢Solves organic waste disposal problem

➢Biogas plants keep the household and surroundings clean and green.

Threats:-

➢Either the organic waste is not continuously fed or over fed into the biogas plant will lead to less or no generation of biogas and results in feeding the Inoculum (cow dung) again in order to make the plant function.

It is very clear from the above mentioned SWOT analysis that the strengths and opportunities are more when compared to the weakness and threats which can be easily overcome through different operation mechanisms

3.1.3. Faecal sludge generation

According to the water research commission in 2012, a typical adult excretes an average of 0.4 kg of faeces per day, which comprises 0.1 kg of dry mass if the moisture content, which comprises 70-80 %, is removed. Approximately 80-90 % of faeces is organic matter which can degrade, and can be broken down as follows:

• undigested fibre: 30 %

• bacteria (mostly non-viable): 30 %

• lipids (fats): 10-20 %

• protein: 2-3 %

• some digestive residuals and GI shed-epithelium, trace amounts of virus, hormones, antibiotics

An adult also passes about 1.5 litres (1.5 kg) of urine per day, comprised of:

• 1.4% inorganic electrolytes (such as Na, K, Cl, SO_4, Mg, P)

• about 1.3 % urea ($CO(NH_2)_2$)

• about 0.54 % organics + 0.4 % organic ammonia salts; and

• water

This implies that an average family of 6 people can produce

6 x (0.4 kg faeces + 1.5 litres of urine equivalent to 1.65 kg of water + 10 kg of water for cleaning) = **72.3 kg of faecal sludge.**

3.1.4. Generation frequency

Table 9: Rapid rate of population growth in Yaoundé (Macrotrends, 2021)

Year	Population	Growth Rate
2021	**4,164,000**	**4.31%**
2020	**3,992,000**	**4.45%**
2019	**3,822,000**	**4.54%**
2018	**3,656,000**	**5.70%**
2017	**3,459,000**	**5.68%**
2016	**3,273,000**	**5.68%**
2015	**3,097,000**	**5.70%**
2014	**2,930,000**	**5.66%**
2013	**2,773,000**	**5.72%**
2012	**2,623,000**	**5.68%**
2011	**2,482,000**	**5.66%**

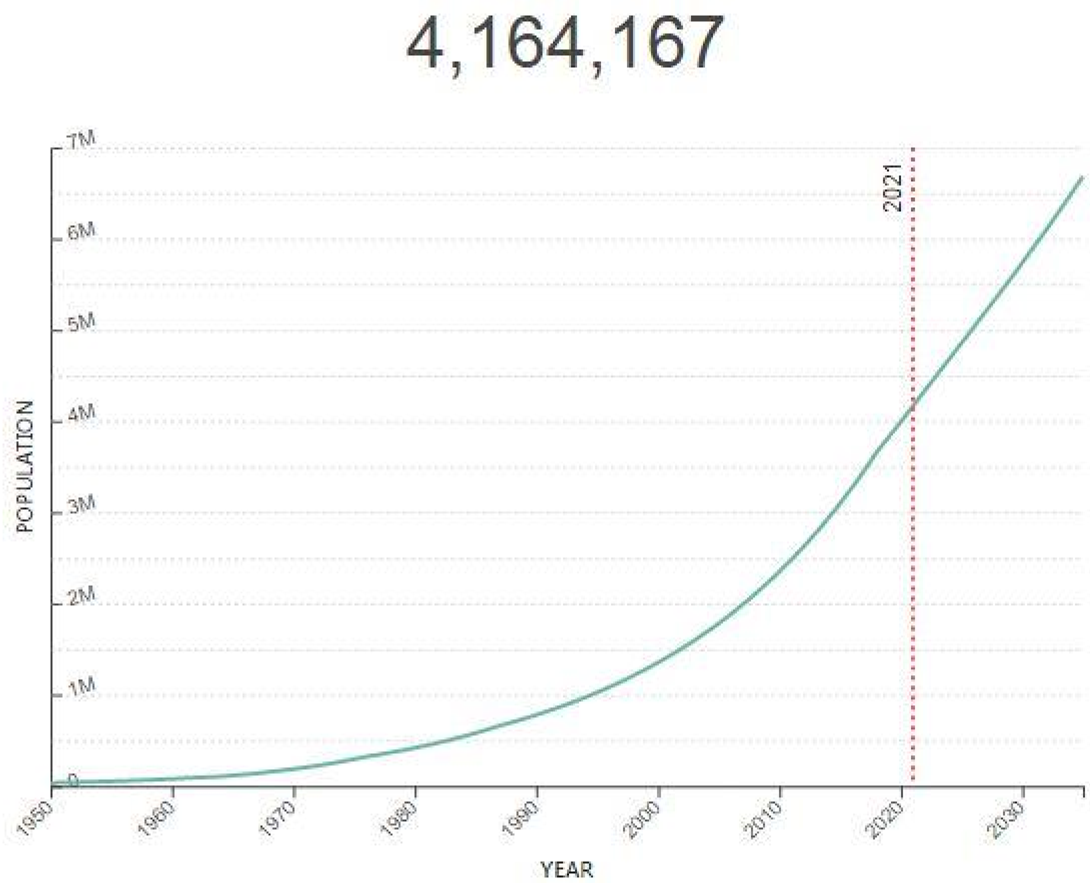

Figure 24: Yaoundé Population Data (Urban Area)

(Worldwide population review, 2021)

Averagely, there are 5-7 people per household in a town of 4,164,167 inhabitants implying 4,164,167persons x 12.05kg/person /day= 50,178,212.4 kg/day = 50,178 tons/day of faecal sludge. So much waste to be valorized by at least a greater part of the city's population for huge benefits.

3.1.5. Design of biogas plant

1. Laboratory results

The samples collected from three (03) septic tanks of different levels of filling were taken to the National Laboratory of Diagnostic Analysis of Agricultural Products and Inputs and the results from the analysis on the waste carried out in the lab are elaborated on the table below.

Table 10: Some characteristics of waste collected

Sample	%DM	%VS	N (g/kg)	C (g/kg)

Sample 1	19.24	79.33	1.16	54.21
Sample 2	27.57	82.51	1.54	43.77
Sample 3	30.90	84.29	3.88	68.40
Mean	25.90	82.04	2.19	55.45

Where, % DM represents the dry mass as a percentage of the original substrate

% VS represents the percentage of volatile matter in relation to the dry matter.

N (g/kg) represents the nitrogen content in g per kg of the original substrate

C (g/kg) represents the carbon content in g per kg of the original substrate

The C/N ratio is = 25.67

This ratio conforms as it exists between 15 and 30 % (C. Rose, A. Parker, 2015).

The values of the dry mass (25.90%) and volatile matter (82.04 %) are equally in conformity as shown in the review.

All these show that the waste is semi solid and wet digestion can be carried out. This permits us to say the waste from household pretreatment tanks is suitable for anaerobic digestion. With these anaerobic conditions being favourable, the risks of inhibition of the digester are reduced. Therefore, production of biogas in homes and institutions is justified.

1. Organic loading rate Q

The waste from a household could be estimated as follows:

Daily, 1 person produces 0.4 kg of excrement + 1.5 litres of urine (1 litre of urine ≈ 1.1 kg of water) + 10 litres of water for cleaning (10 kg) = 12.05 kg

An average household with 6 persons thus produces **72.3 kg** of feacal sludge.

In this work, it is assumed that all the waste and water used afterwards for cleaning will be collected immediately into the pretreatment (septic) tank. The organic loading rate is therefore given by

Q = 72.3 kg/day ×22.57 % × 78.38 %

= **12.81 kg/day**

Table 11: Production of biogas, methane and production relative to LPG

Daily production of bio-degradable waste per day(kg)	**Daily production of biogas (litres)**	**Daily production of methane (litres)**	**Daily production relative to LPG (kg)**
12.81	1918.52	1151.11	0.58

2. Dimensions of the pre storage pit

$$\text{Volume} = 2 \times \frac{\boldsymbol{daily\ mass\ of\ biodegrable\ waste}}{\boldsymbol{\rho_{waste}}}$$

$$= 2 \times \frac{72.3kg}{1003kg/m^3} = 0.144\ m^3$$

= 144 litres

$\boldsymbol{\rho_{waste}}$ is the density of the biodegradable waste of the faecal sludge and is determined by weighing the mass of the waste of a particular volume. The volume of the pre storage pit will also be as a function of the quantity of waste released per day at the slaughterhouse which increases with time as demand for meat is always on the rise.

The quantity of waste produced keeps increasing with time as was shown in the population table above. From the year 2011 to 2021, the population of Yaounde is shown to be increasing at an mean rate of 5.38 % and at the same time 3.75 % when forecasted from 2021-2031.

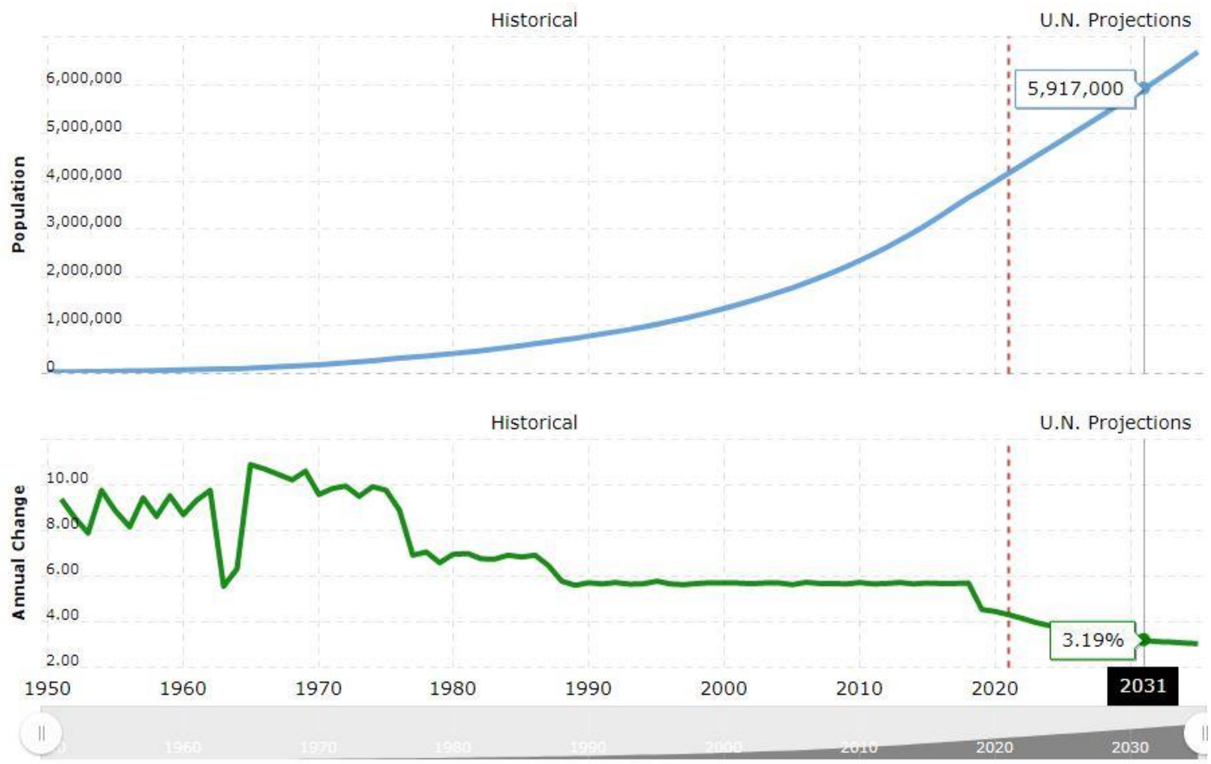

Figure 25: Population forecast of Yaoundé (United Nations)

The average number of persons per household therefore changes to 7.

Therefore, daily faecal sludge production = 7 x 12.05 = **84.35 kg of faecal sludge.**

The storage pit therefore requires a new volume

Volume = 2 x 84.35kg / 1003kg/m^3= **0.168 m³ = 168.2 litres**

The pre storage pit will be considered taking the form of a rectangular parallelepiped constructed with concrete (as concrete is cheaper than steel) and will have the following dimensions;

Length = 0.7m Width= 0.6m Height= 0.4 m

3. Dimensioning the digester

Considering that the retention time is 25 days, the total volume of the digester is given by

Volume = retention time x daily volume of the waste

= 25 x daily mass of substrate / density of substrate

The digester has to be capable of treating the increasing quantity of sludge produced. Considering the mass calculated in a horizon of 10 years, the total volume of our digester will be given by

Total volume = 25 x 84.35 kg / $1003 kg/m^3$ = **2.102 m³ = 2102 litres**

- **Dimensioning the cylinder**

Considering the points shown in the methodology of this work, the internal height of the cylinder is equal to the internal radius of its base Hint = Rint and its internal radius is given by;

Rint = **0.83 m**

This implies that the internal radius and the internal height of the digester are equivalent to 0.6m and internal height of the conical part is 0.41m

Total internal height of the digester = 0.83 + 0.41 = **1.24 m**

- **Dimensions of the cone**

The height of the cone is given by hint = Hint / 2. Therefore its value is given as **0.41 m**

4. Dimensioning the storage tank

The volume of this storage tank is given by

Volume of storage tank = **30 x 84.35 kg / $1003\ kg/m^3$ = 2.523 m³ = 2523 litres**

It will be constructed in the shape of a rectangular parallelepiped with dimensions given as;

Length = 1.6 m, Width = 1.6 m, Height = 1 m

Table 14 below shows a summary of the different dimensions of pre storage pit, storage tank and digester

Table 12: Some plant dimensions

Dimensions of pre storage pit	**Dimensions of storage tank**	**Internal Dimensions of digester**	
		Cylinder	Cone

Length (m)	Width (m)	Height	Length (m)	Width (m)	Height (m)	Height (m)	Radius (m)	Height (m	Radius (m)
0.7	0.6	0.4	1.6	1.6	1	0.83	0.83	0.4	0.83

It should be noted that the dimensions of the digester given above are the internal dimensions of the digester. The external dimensions of the digester obviously take into account the dimensions of the steel and polystyrene which will be used to coat the digester against heat losses.

The external height of the digester will therefore be given as

$H_{external}$ = 0.83 +0.41 + 2(0.1 + 0.008) = **1.46 m**

5. Dimensioning the gasometer

It is given by Volume of gasometer = 5 × 1.918/24

= **0.4 m³ = 400 litres**

One gasometer will be considered with flexible membranes of spherical shape of volume **0.5 m³.**

6. Evaluation of the thermal energy needs of the digester

a) Case of energy losses due to conduction in the digester

In case of heat losses in the digester, the digester will be coated with a layer of stainless steel and polystyrene to absorb all heat losses. The parameters of the steel and polystyrene are shown in the table below.

Table 13: Parameters of the stainless steel and polystyrene

Thickness of stainless steel	**Thickness of polystyrene**	**Thermal conductivity of steel**	**Thermal conductivity of polystyrene**
0.008 m	0.1 m	15 W/m K	0.03 W/m K

Considering the above parameters we obtain the following

$R_{thermal\ resistance\ of\ the\ steel\ on\ the\ lateral\ side}$ = 1.1 × $10^{-6}m^2$ K / W

$R_{thermal\ resistance\ of\ the\ steel\ on\ the\ upper\ side}$ = 2.2 × $10^{-6}m^2$ K / W

$R_{thermal\ resistance\ of\ the\ polysterene\ on\ the\ lateral\ side}$ = 6.79 × $10^{-3}m^2$ K / W

$R_{\ thermal\ resistance\ of\ the\ polysterene\ on\ the\ upper\ side}$= 1.35 × $10^{-2}m^2$ K / W

$\boldsymbol{G_{ms}}$$_{,heat\ generating\ factor\ of\ steel\ in\ the\ conical\ part}$ = 9.82m

$R_{thermal\ resistance\ of\ steel\ conical\ part}$ = 9.84 × $10^{-7}m^2$ K / W

$\boldsymbol{G_{mp}}$$_{,heat\ generating\ factor\ of\ polystyrene\ in\ the\ conical\ part}$ = 9.89m

$R_{thermal\ resistance\ of\ polysterene\ conical\ part}$ = 6.07 × $10^{-3}m^2$K / W

The total thermal resistance is therefore given by

$R_{total\ resistance}$ = 2.59 × $10^{-3}m^2$ K / W

Knowing the temperature difference between the outside and the inside of the digester, the heat loss flow is given by

$$\boldsymbol{Heat_{loss}} = \frac{\boldsymbol{T_{digestion}} - \boldsymbol{T_{exterior}}}{\boldsymbol{R_{total\ resistance}}} = \frac{\boldsymbol{55-24}}{\boldsymbol{0.00259}} = 11969 \text{ Wh}$$

Daily energy losses are given as

$\boldsymbol{Energy_{loss}}$ **per day =** $\boldsymbol{Heat_{loss}}$**x 24 = 287.25 kWh**

The movement of the gas from the digester to the storage tank allows some portion of the digestate back into the digester. This backward movement causes agitation in the sludge and increases the rate of the reaction implying agitation can compensate for the energy loss.

7. Dimensioning the gas treatment unit

The biogas drying and compression unit must be able to process the biogas produced by the maximum amount of daily organic waste to be treated. In this case its 84.35 kg. This unit therefore must be able to process biogas with a flow of

Flow = $\frac{Daily\ biogas\ production}{24} = \frac{1.918}{24} =$ **0.08 m³/h**

8. Daily gas consumption,

A gas bottle containing 12.5 kg of LPG can carry a family of 6persons for at least 30 days.

$\Rightarrow \frac{12.5}{30}$ = 0.42 kg of LPG is used daily.

Since 1 kg of LPG = 2 Nm³ of methane,

$\Rightarrow 0.42\ kg\ of\ LPG\ x\ 2 = 0.84\ Nm^3\ of\ methane$

Daily gas consumption = 0.84 Nm³

To show a surplus, **Daily production – Daily consumption** = 1.151 Nm³ – 0.84 Nm³

= **0.311 Nm³**

Moreso, the subsequent future increase in number of people per home will increase the surplus value.

Ultimately, the project will constitute of

- 1 pre storage pit of parallelepiped shape with a volume of 1.68 m³.

- 1 stainless steel digester covered with polystyrene comprising a cylindrical upper part of volume 1.8 m³ and a conical lower part of volume 0.37 m³.

- A rectangular concrete storage tank with a unit volume of 2.523 m³.

- A spherical gasometer consisting of 2 double flexible membranes of unit volume 0.5 m³

- A biogas drying and compression unit capable of treating biogas with a flow rate of 0.08 m³/h

3.1.6. Economic and Environmental analysis.

Economic analysis

This economic analysis of this project will be on the following parameters

- **Cost of investment** = 600,000 FCFA

Cost of compost Sale = 72.3 x 0.35 x 365 x 10

= 92,360 FCFA

Yearly average purchase of LPG = 78,000 FCFA

Environmental analysis

The main environmental benefits obtained from biogas plant include;

- A major decrease in air pollutants and GHG emission in the atmosphere as CH_4 is a more severe GHG than CO_2 and is generally released into the atmosphere during land application of animal and human effluents without anaerobic treatment. Therefore, its capture in the AD process and its use as a fuel would significantly reduce the net GHG production.
- Also, the risk of pollution and eutrophication of the deep surface waters into which a portion of sludge was deposited into is drastically reduced.
- Atmospheric emissions of odorous substances too are avoided as AD has the potential to stabilize and deodorize animal and human waste as the treatment produces a residue almost completely devoid of malodorous substances.
- Digestate can effectively be used as organic fertilizer, compost, livestock bedding, fuel pellets and construction material (medium density fibreboard and fibre /plastic composite materials).

Conclusion

The aim of this section was to explicitly demonstrate the results gotten from different pretreatment tanks and dimension an anaerobic digester for at least 6 persons/house in the city of Yaoundé. It therefore consists of the results from the questionnaires that were distributed, the results of the analysis from the lab the data obtained from the 3 different pretreatment tanks, the data from the renewable energy course by Prof Nde Divine Bup which permitted the dimensioning of the pre-storage pit, anaerobic digester, storage tank, pump and gasometer and also in estimation of the quantity of treated gas to be obtained.

3.2. DISCUSSION

3.2.1. Reminder of the main results of the study

The various analysis of the project were made based on the fact that in the first year of the project, the quantity of the biodegradable waste treated is 72.3 kg and this quantity increases by 12.05 kg annually from the second year to the 10^{th} .

3.2.2. Results of the analysis from the lab

The results of the waste from the samples taken to the National laboratory of diagnostic analysis of Agricultural products and inputs allow us to say that the faecal sludge of an average septic tank in Yaoundé has a dry matter of 25.90 %, a volatile matter content of 82.04 %, a Carbon content of 55.45 kg/kg and a nitrogen content of 2.19 kg/kg giving a C/N ratio of 25.67. This explains that the waste is suitable for good anaerobic digestion.

3.2.3. Results of sizing

The energy recovery from faecal sludge in the city of Yaoundé has led us to design an anaerobic digestion and biogas recovery unit. The components are as follows

- 1 pre storage pit of parallelepiped shape with a volume of 1.68 m^3.

- 1 stainless steel digester covered with polystyrene comprising a cylindrical upper part of volume 1.8 m^3 and a conical lower part of volume 0.37 m^3.

- A rectangular concrete storage tank with a unit volume of 2.523 m^3.

- A spherical gasometer consisting of 2 double flexible membranes of unit volume 0.5 m^3

- A biogas drying and compression unit capable of treating biogas with a flow rate of 0.08 m^3/h

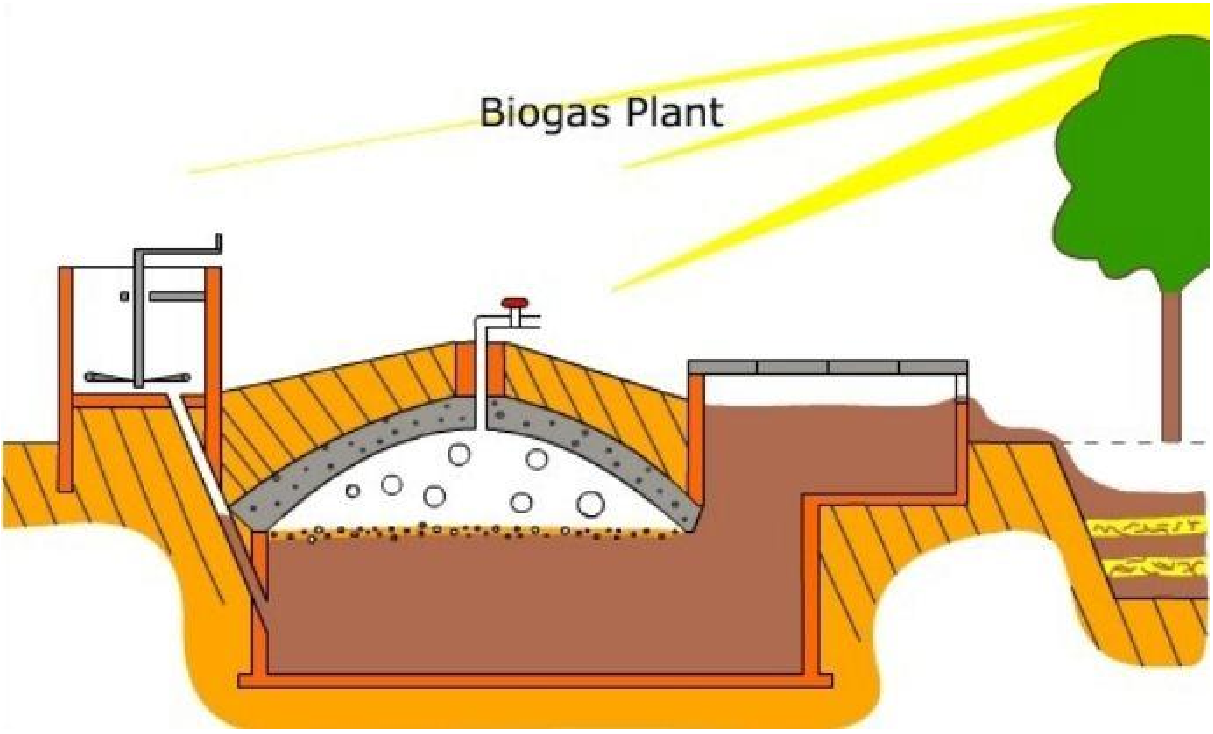

Figure 27 : Biogas tank demonstration

3.2.4. Results of the energy aspect

The quantity of primary energy produced first by the project is used in the structure for cooking and as time goes on, the amount of biogas produced will be increasing. Comparing amount of biogas produced daily to the average daily consumption; we notice that the structure may still need extra supplies from the cooking gas vendors when the number of people/workers goes lower than six (6) and a few years after, the structure will be able to solely depend on the output of the system and consider using the project to generate electricity.

3.2.5. Results of the economic aspect

The economic analysis of the project was made considering that the structure uses the electrical energy from the production system and the resulting digestate is dried and put on sale for persons in the agricultural sector.

The total investment into the project on the first year amounts to 600,000 FCFA for operation and maintenance each year. Also, the structure doesn't only benefit from sufficient cooking energy supply to run their daily needs which allows them retain the estimated 78,000 FCFA paid generally per annum to local LPG vendors but also gains an estimated 92,360 FCFA from the sales of compost to those in the agricultural sector on the first year.

$$P_1 = 1 + \frac{78000}{600000}$$

$$= 1.13$$

The project is a value added project with a good profitability index.

The return time of the investment is given as: 600000 / 92360 = **6.5years**

3.2.6. Results of the environmental aspect

By putting in place this project, the amount of greenhouse gases emitted are drastically reduced as well as the effective pollution as a result of the waste disposal in the nearby surroundings. The utilisation of the methane help to protect the atmosphere from global warming since the waste produces methane naturally and it goes up to the atmosphere if not trapped or used, it reduces the use of firewood and the deforestation. The digestate and subsequent compost helps to improve the growth of plants and fish.

Conclusion

In the chapter, the results of the study have been presented including the results from the laboratory experiments and the dimensions of the different compartments of the biogas plant and subsequent energy which will be recovered from the system. The environmental and economic aspects of the implantation of the system too have been elaborated.

On environmental basis the pollution of the immediate faecal sludge is reduced by the containment of the waste and gases constantly been released into surrounding waters enhancing its contamination. This project shows that it is possible to not only obtain enough energy capable of satisfying the biogas needs of numerous homes and institutions but also make profit from the sale of digestate there by validating the assumed hypothes

GENERAL CONCLUSION

Anaerobic digestion, part of an integrated energy recovery management has interesting potential in terms of energy and economics. The bio-methanation technology which was proposed for this work would be a significant and fundamental structural element in sustainable development. It is a technology that makes it possible to reduce the overall environmental impact of the FSM which is mainly organic to be treated and solve the deficits in cooking energy in carrying out the cooking needs of the concerned structure.

The problem of this study was, 'How the production and use of renewable energy be encouraged by transforming FS into clean and sustainable energy?' The main objective was 'to encourage the making and use of renewable energy through small scale production of biogas in an urban area like Yaoundé for a sustainable living'.

Results showed that the biogas feed stock had the following properties; a dry mass percentage of 25.90 %, volatile solid percentage of 82.04 % and a C/N ratio of 25.67 which makes it a suitable candidate for biogas production. In this work, the different compartments of the biogas system namely; the pre storage pit, the digester, the storage tank, the gasometer, the biogas drying and compression unit were successfully dimensioned. It is important to note that the daily production of methane is 78.42 m^3 from 72.3 kg of waste which can be used for more than the estimated amount of time taken to completely empty a bottle of LPG. This also results in 9.236 kg of digestate every year.

On economic basis, the total investment into the project to completion amounts to 600,000 FCFA in the first year including costs for operation and maintenance. The investment has a profitability index of 1.13 as it shows that the project is a value added project. The company will need a period of 6.5 years to regain the initial investment into the system On environmental basis the pollution of the structure and its immediate environment is reduced by the containment and valorisation of the waste which is in some cases released into surrounding waters enhancing its contamination or dumped in illegal sites out of town. This project shows that it is possible to not only obtain enough energy capable of satisfying the cooking needs of the concerned structure but also make profit from the sale of digestate there by validating the idea of a good deal.

SUGGESTIONS

- Sensitization of the individuals and personnel involved in any form of FSM activity on the importance and necessity of the management of waste and if possible encouraged to engage in the process of anaerobic digestion of this waste.
- A co-digetion process can be adapted as it would increase the biogas yield and go a long way to managing the biodegradable household domestic waste.

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APPENDICES

APPENDIX 1

Questionaire for a research in Master Degree in Environmental Engineering
I am Eyong George Ayuk a level 5 student of National Advanced School of Public Works, Yaoundé. In order for me to realize my Master thesis and would plead for you to lend me 5 minutes of your time to respond on the sanitation and functioning of your structure.

NB: Every information offered in this questionnaire will strictly be used for the analysis of this project

1. Is this a government owned or private structure ?...
2. What position do you hold in this structure?
   a- Administrative personnel b- worker c- family member d- other.
3. Can you estimate the number of persons that work/live in this structure ?
   a- Less than 10 b- 10 to 50 c- 50 to 100 d- more than 100
4. How often do people come work/ live here?
   a Everyday b- 2 to 3 times a week c- Once a week d- Once a month
5. What average age range works/lives here on a daily basis?
   a- 1-15 b- 11-30 c-31-45 d- 45-60
6. How many times do you eliminate your waste while here?
   a- Never b- Once c- Twice d- Thrice e- More
7. What are the different processes you carry out in the waste elimination?
   ....
   ....
   ....
8. Can you identify the different waste for each process and if possible the quantity?
   a) Urine
   b) Faeces
   c) Both
   d) More

……………………………………………………………………………………

………………………………………………………………………………………………

…………………………………………………………………………………………

9. Can you estimate the amount of water used daily in this structure?

   a- Less than 100liters b- 100 to 500 liters c- 500 to 1000liters d- more than 100liters

10. For all other waste types, what is the range of the quantity of eliminated waste per day?

    a- 0 to 10 litres b- 10 to 20 litres c- 20 to 30 litres d- more than 30

11. Do you have systems put in place to collect waste?

    a- Yes b- No

12. How is this waste collected?

    a- Collectively b- Separately

13. What systems have been put in place to collect this waste?

    a- Drainage pipes and gutters b- water pipes for flushing c- channel to septic tanks

    Others...

    ....

    ....

14. What is the collection frequency?

    a- Daily b- twice a week c- once a week

15. What do you do with the different waste after they have been collected?

    - Dump in HYSACAM bins and dump sites
    - Channel to septic tanks
    - Release into nearby waters
    - Other

    Explain...

    ....

    ....

16. What quantity of water is used in this structure daily?

    a. 0 to 10 litres b. 10 to 50 litres c. 50 to 100 litres d. more than 1000 litres

17. What activities or appliances in this structure require the use of cooking gas?

    a- Cooking as plate b- Baker c- Microwave

    Others...

    ....

    ....

18. And what is the source of the cooking gas used? ....

19. What consumption quantity is recorded monthly?..
20. Do you have any idea on biogas production from organic waste?
    a. Yes b. No. If yes, would you like to implement it in your structure.

THANKS