DEVELOPMENT OF A MODEL FRAMEWORK FOR SIMULTANEOUS SYNTHESIS AND SELECTION OF ANAEROBIC DIGESTER STRUCTURES

By

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ABSTRACT

The anaerobic treatment process has increasingly been recognized as an efficient technology for sustainable nutrient recovery, renewable energy generation, and environmental sanitation due to its strong potential to mitigate current energy resource and climate change challenges. However, the success of industrial-scale anaerobic digestion is only possible if the following two prerequisite factors are met: availability of a sustainable supply of organic feedstock and design of optimal process configurations containing appropriate digester subunits that are well adapted to the characteristics of the feedstock of interest. A lot of combinations of the fundamental anaerobic digester types exist, which becomes impossible to test all the possibilities in order to determine the one with the absolute best performance. This study did not focus attention on devising new digesters with the aim of improving the performance of the system, but rather optimally arranged some combinations of plug flow reactors (PFRs) and continuous stirring tank reactor (CSTR) systems. The objective of study was to establish a framework based on multi-criteria decision analysis, for optimal selection of anaerobic digesters and practical implementation of digester networks, which is amendable to any substrate and digester configuration. Anaerobic treatability study was performed using pineapple waste, pig waste, abattoir waste and food waste to obtain cummulative biogas yield curves followed by development of the digester configurations using the attainable region technique. A hybrid Analytical Hierachy Process and Fuzzy Technique for Order Preference by Similarity to Ideal Solution was used in the selection of plug flow anaerobic digesters for the configurations. The following biogas volumes were obtained at the end of the 30 days retention period; $0.014\,m^3$ for pig waste, $0.012m^3$ for abattoir waste, $0.009\,m^3$ for food waste and $0.006\,m^3$ for pineapple waste. Quantity of feedstock used was 5kg per sample. A novel framework for the selection of multi stage anaerobic digesters has been presented. Optimal digester configurations obtained differ based on substrate used. The selected plug flow anaerobic digesters for subunit were Expanded Granular Sludge Bed for scenario 1, scenario 2 and scenario 3 were Anaerobic Baffled Reactor.

KEYWORDS: Analytical Hierarchy Process, Anaerobic Digestion, Attainable Region, Fuzzy Logic, TOPSIS, Scenario Planning

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LIST OF ABBREVIATIONS AND ACRONYMS

ABR	Anaerobic Baffled Reactor
ACR	Anaerobic Contact Reactor
AD	Anaerobic Digestion
AF	Anaerobic Filter
AFBR	Anaerobic Fluidized Bed Reactor
AHP	Analytical Hierarchy Process
APFR	Anaerobic Plug Flow Reactor
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
C:N	Ratio of Carbon to Nitrogen Ratio
CSTR	Continuously Stirred Tank Reactor
EGSB	Expanded Granular Sludge Bed Reactor
FNIS	Fuzzy Negative Ideal Solution
FPIS	Fuzzy Positive Ideal Solution
DM	Dry Matter
HRT	Hydraulic Retention Time
HW	Human Waste
ICR	Internal Circulation Reactor
LPG	Liquefied Petroleum Gas
MA	Mineral Ash
MC	Moisture Content
MCDA	Multi-Criteria Decision Analysis
MCFC	Molten Carbonate Fuel Cell
ODM	Organic Dry Matter
OLR	Organic Loading Rate
OMW	Organic Municipal Waste
PAFC	Phosphoric Acid Fuel Cell
TOC	Total Organic Carbon
TOPSIS	The technique for order preference by Similarity to Ideal Solution
TS	Total Solids
UASB	Up-Flow Anaerobic Sludge Blanket Reactor

VFA	Volatile Fatty Acids
VS	Volatile Solids
VS	Volatile Solids
VSS	Volatile Suspended Solid

DECLARATION

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has to a substantial extent has been accepted for the award of any other degree or diploma at Kwame Nkrumah University of Science and Technology, Kumasi or any other educational institute, except where due acknowledgment has been made in the thesis.

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DEDICATION

I dedicate this thesis to the Ossei-Bremang Family.

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

The anaerobic waste treatment process is an well known technology in the area of renewable energy recovery, sanitation and nutrient recovery with a lot of prospects (Mao *et al.*, 2015). The process is highly complex, limited by different conditions which include waste characteristics, reactor configuration, operational parameters, environmental factors such as pH and temperature as well as toxins (Nwaigwe and Enweremadu, 2015). Due to the aforementioned reasons, appropriate design of the anaerobic digester is key to optimal operation of anaerobic digestion, as it makes an appropriate microbiological condition for anaerobic microorganisms to turn and produce biogas (Fedailaine *et al.*, 2015). Nevertheless, the success of industrial-scale anaerobic digestion is only possible if the following two prerequisite factors are met: availability of a sustainable provision of organic feedstock and design of optimal process configurations containing appropriate digester subunits that are easily adapted to the characteristics of the feedstock of interest. However, a full diversity of anaerobic digester systems have been developed, which can be classified into three groups: a) conventional digesters such as ASBR, CSTR, and PFR (Manthia *et al.*, 2018), b) sludge retention digesters such as ACR, UASB, UASSR, ABR and ICR and c) membrane digesters such as AF, EGSB and AFBR. Neba *et al.* (2019), mentioned that the PFR and CSTR are at the extremes of mixing and reaction. It further explains that different combinations of these digesters will provide different extents of mixing and reaction in the entire system. In essence, all high rate digesters (sludge retention and membrane reactors) provide separation in addition to mixing or reaction.

A lot of research work confirms that when the reaction mechanism of anaerobic digestion is complicated, the performance can be reached in a reactor network. (Mao *et al.*, 2015). It is evident that each anaerobic digester has different operating features often making them more preferred for the treatment of certain kind of waste with special characteristics, and thus using a single digester in one configuration could hinder the possible combination of pathways, which consequently affects performance. The performance of the anaerobic treatment process further depends on three fundamental processes, mixing (performed by CSTR) reaction (performed by PFR) and separation performed by high rate systems (Neba *et al.*, 2019). This involves the problem of multiple results when seeking to couple anaerobic digesters in multistage operations. Optimal synthesis of anaerobic digester structures based on model-based approaches may present designs that systematically work out specific operational challenges as opposed to systems designed using empirical approaches (Metzger *et al.*, 2007). Neba *et al.* (2019) further applied attaianble region theory to substrates such as the chicken, horse, goat, swine and diary manure to optimize the methane production of these substrates. This novel study came up with different configurations which was made of combinations of CSTRs and PFRs for the optimization process without providing a systematic way for the selection of PFRs to include in the configuration.

This research therefore, sought to apply the attainable region technique coupled with Multi-Criteria Decision Analysis Tools (MCDA) methods which are powerful decision-making tools as ascribed by Velasquez and Hester (2015) to select a digester which is most preferred for the treatment of substrates in the scenarios established in the study. A hybrid of AHP/FUZZY TOPSIS was incorporated because the AHP has an accurate weighing strength and an ability to share with larger problems and also bear large data networks and complex decision problems with various intangible criteria. Fuzzy Theory discovered by Zadeh, (1965) on the other hand was applied in this study to cater for the vagueness and ambiguity in the decision making process which would have resulted from the complex nature of the qualitative data obtained from the literature on the various data types of anaerobic digesters (CSTR, ABR, EGSB, APFR, UASB, AF and ACR) under consideration in this study. TOPSIS technique was used for the ranking of alternatives. Thus, it aided in the ranking of the most appropriate digester for each of the scenarios (Pavić and Novoselac, 2016). The current study designed to produce a conceptual, theoretical framework coupling the AR technique with multi-criteria decision-making tools for simultaneous synthesis and selection of anaerobic digesters.

1.2 Problem Statement

In anaerobic waste treatment, there are different types of digesters each with different characteristics often making them more tolerable to treat specific effluents rather than others (Neba *et al.*, 2019). Utilizing one reactor in one configuration may limit it’s performance which involves the entire operation because the bacteria acting on the various phases of the anaerobic digestion process require special operating conditions to be able to work efficiently. This confirms several studies found in the literature that reported that the best performance of a complex reaction process is often achieved in a reactor network or reactor structure. The study by Neba *et al*., (2019) is the first study to apply attainable region technique to anaerobic digestion waste treatment process to maximize methane production. Even though they came up with different configuarations for the optimization process which included combinations of CSTRs and PFR in a single subunit for both batch and continuous operations, it did not give a systematic way for the selection of a plug flow digester to be used in the configuaration. The challenge now is to know which specific type of plug flow digester to use in configuration for the waste treatement process and the precise number of digesters to include in a specific configuration.

1.3 Justification of the Study

This study presents a systematic, dependable and robust methodological framework for the selection and synthesis of anaerobic digesters as a major innovation in extending the use of MCDA and AR in the selection of anaerobic digesters. This would work out more operational challenges in anaerobic digestion associated with the traditional multi-stage digestion system presented by researchers such as Strezov and Evans (2012). The framework is founded along the concept of Fuzzy Multi-Criteria Decision Making (Velasquez and Hester, 2013).

1.4 Objective

1.4.1 Main Objective of Study

The main objective of study is to establish a framework based on multi criteria decision making analysis (MCDA) for optimal selection and synthesis of anaerobic digesters which is amendable to all substrates.

1.4.3 Specific Objectives

The specific objective of the study were:

a) To characterize the organic waste and perform treatability studies.
b) To produce a general optimal digester structure.
c) To perform a multi-criteria analysis to select the most appropriate plug-flow digester for use in the digester structure.

1.5 Scope of the Study

The study was intended to develop a framework that couples attainable region theory and fuzzy multi-criteria decision making to synthesize in a systematic way, anaerobic digester structures for three different scenarios: renewable energy generation, sustainable nutrient recycling, and waste treatment. Firstly, ponderous substrate characterization followed by anaerobic treatability studies conducted on four different organic substrates. Secondly, the experimental measurements of cumulative biogas production were used to construct two-dimensional attainable regions, which are then interpreted into optimal digester structures. This digester structures are made up of different combinations of plug flow and continuous stirred digesters. Thirdly, the fuzzy MCDA technique is applied to select and integrate digester subunits in order to obtain optimal digester structures for the three practical scenarios considered. Finally, a schematic model of the systematic methodological hybrid method was developed, for easy reference that would be made by other researchers.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Globally, researchers have carried out studies in a lot of ways to address enevironmental sanitation, to ensure clean and affordable energy and clean water as part of the Sustainable Developmentm Goals (SDGs) through waste management which contributes partially to these goals. This Chapter provides information on wastes, the circumstances that informs the need for anaerobic waste treatment (Scenarios) and the numerous limitations one may encounter in the Anaerobic treatment of wastes. This chapter also discusses the types of anaerobic digesters, classification of the digesters (plug flow reactors, continuous stirring tank reactors, and batch) and factors impeding the performance of anaerobic digesters by other authors. The chapter would also review literature comprehensively on the reactor configurations and its application to the AD process and the MCDA tools which would be used for the selection process (Vinogradova *et al.*, 2018).

2.2 Principle of Anareobic Digestion process

Anaerobic microbiological decomposition is a complex process whereby micro-organisms obtain energy and grow by metabolizing organic material in an environment in the absence of oxygen which results in the production of methane (Mes *et al.*, 2013).

The Anaerobic Digestion Process follows these systematic processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Despite the successive steps, hydrolysis is generally considered as rate-limiting stage (Orhorhoro *et al.*, 2017). Degradation of both insoluble organic material and high molecular weight compounds such as nucleic acids, lipids, proteins, and polysaccharides into soluble organic substances (such as amino acids and fatty acids) occurs at this stage. The acidogenesis stage, which is the second stage, further split the components formed during hydrolysis to produce VFA by acidogenic (or fermentative) bacteria (Okonkwo *et al.*, 2013). The third stage in the reaction is acetogenesis in which acetogens digest the higher organic acids and alcohols produced by acidogenesis to produce mainly acetic acid, carbon dioxide and Hydrogen. At the final stage, methanogenesis produces methane by two groups of methanogenic bacteria: the first group breaks acetate into methane and carbon dioxide, and the second group utilizes hydrogen as an electron donor and carbon dioxide as an acceptor to produce methane (Dewil *et al.*, 2009).

2.3 Factors affecting the AD process

2.3.1 pH value range

The pivotal factor in the anaerobic digestion process is the pH value. Substrates with an optimum range value of pH 7 have higher degradation efficiency and biogas production yield as compared with other pH range values and this has been proved experimentally. An acidic environment inhibits the growth of the methanogens which affects methane production. Moreover, higher pH value thus, a pH more than 7.5 and towards 8 can generate a proliferation of methanogens which inhibits acetogenesis process (Singh *et al.*, 2018).

2.3.2 Hydraulic retention time

An important design factor that contributes to a successful AD process is the average amount of time the sludge stays in the digester. An optimal retention time gives good results such as higher biogas yield, higher destruction of oxygen demand, total solids, volatile solids, pathogens and lower emissions of greenhouse gases and odors (Chen *et al.,* 2008).

2.3.3 Temperature

Biogas plants are mostly mesophilic or thermophilic. The former achieves an optimal result in a temperature range of 35 to 41 °C, whereas the latter prefers 57 °C and more. Temperature fluctuations are threatening condition for the methanogenic bacteria. The temperature of the anaerobic digestion process should, ideally, be kept constant to within a maximum of ± 1 °C. Temperature plays a crucial role in the entire process (Hu *et al*., 2008).

2.3.4 Loading rate

A specific loading rate of the digester is an important factor to consider in waste treatment. It can be recognized from the number of volatile solids in the digestion of an AD system which can be viable as an input in the arrangement. A higher loading rate may result in low or average biogas production. Thus overloading usually occurs when there are degrading or inhibiting substances present in the system such as insoluble fatty acids which can cause lagging in the path of biogas production. High loading in simple words causes an increment in the number of acidogenic bacteria which stimulates pH fall and thus results in the elimination of methanogenic bacteria or methane-producing micro-organisms hence causing the performance of the system to go down (Singh *et al.*, 2018).

2.3.5 Carbon to Nitrogen ratio

The C:N ratio presents the relationship between the amount of carbon and nitrogen in organic materials to feed into an anaerobic digester. Nutrient deficiency and ammonia inhibition in a fermentation system cannot be regulated without having a knowledge of the C:N ratio (Mao *et al.*, 2015). Optimal C:N ratios in anaerobic digesters are often between 16 and 25 (Vögeli *et al.*, 2014). A high C:N ratio indicates the rapid uptake of nitrogen by methanogenic bacteria, which then results in lower gas production. On the other hand, a low C:N ratio causes ammonia build up.

2.3.6 Agitation or slurry stirring

Agitation is the process which causes disturbance or turbulence to the slurry in a digester. Strezov and Evans, (2013) grouped the methods of agitation into passive and active agitation. Active agitation/ stirring is causing turbulence in the digester by using manual, mechanical, hydraulic or pneumatic stirring equipment whiles the passive agitation occurs whenever fresh feedstock is fed into the digester.

Slurry stirring is very important for the microorganism community in an anaerobic digestion system for several reasons. Stirring when efficiently done, increases the rate of biogas production by 10 – 15% House, (2010) and 50% in some instances (Vögeli *et al.*, 2014). Other reasons why active stirring must be managed in a digesters are its tendency to: a) facilitate the up-flow of gas bubbles and homogenize the distribution of heat, b) bring the micro-organisms in contact with the new feedstock particles and c) prevent the formation of swimming layers (scum) and of sediments and nutrients through the solid volume of substrate (De Mes *et al.*, 2003).

2.4 Advantages and disadvantages of Anaerobic digestion

The adavatages and disadvantages of anaerobic digestion are seen below.

2.4.1 Advantages of biogas

There are a lot of exciting benefits associated with Anaerobic digestion enlisted as follows: It is a source of renewable energy because biogas would never deplete until the waste production is ceased (Orhorhoro *et al.*, 2017). Its energy source is also free and reduces the demand on fossil fuels, Biogas is regarded as non-polluting in nature (Singh *et al.*, 2018). Since the production of biogas does not require any oxygen, resources are conserved by not consuming any further fuel. It also has the propensity to reduce deforestation and any sort of indoor air pollution (Singh *et al.*, 2018). It reduces emissions of greenhouse gases. When the system is managed efficiently, it improves methane production and does not emit toxic substances into the atmosphere (Kiran *et al.*, 2016). This contributes to climate change. Setting up Biogas plants creates a number of employment opportunities for thousands of people (Mwangi, 2016).

2.4.2 Disadvantages of biogas

The level COD of the substrate must be strictly monitored if digester performance is not to be adversely affected. The anaerobic digestion process is undertaken by a synergistic consortium of micro-organisms and the interdependencies of the facultative anaerobic micro-organisms require a delicate equilibrium between the organisms and the process (Chen *et al.*, 2008). Also, a disturbed system reduces the performance of the digestion process thus COD removal and biogas production rate as reported by Schirmer *et al.* (2014) and in uncontrollable circumstances, it causes a complete equipment failure of the entire process. In addition to the already mentioned, the operation of an AD system cannot be handled as a ‘black box’ because of the delicate nature of anaerobic digestion. This connotes that in-depth understanding of the niceties of the procedure is required for successful functioning. Last but not the least, the AD requires huge capital and performance cost. This reason compels inhabitants of developing countries to integrate AD process into their scheme sooner than employing it as an energy source alone. (Perez and Herrera-robledo, 2018).

2.5 Technologies of anaerobic digestion

The technologies of anaerobic digester configurations have been grouped into sludge retention, conventional and membrane reactors based on the research findings by Mao *et al.* (2015) as viewed in the schematic diagram below.

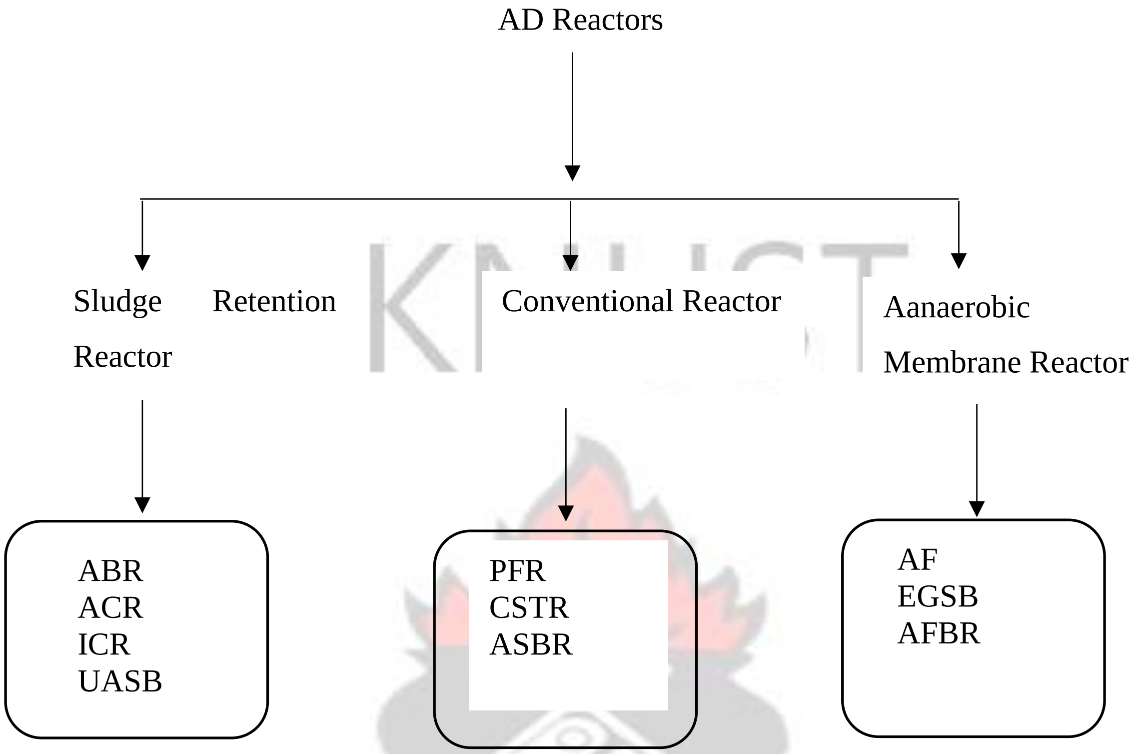

Figure 2.1: Technologies for anaerobic reactors

2.5.1 Sludge retention reactors

2.5.1.1 Anaerobic baffled reactor

The very first design of the anaerobic baffled reactor was developed by Bachmann and McCarty. It is depicted as a series of UASBs (Liu *et al*., 2010). The ABR design makes use of a series of vertical baffles to mount pressure on the liquid waste which flows under and over them as it works through the inlet to outlet as shown in Fig 2.2 the liquid waste comes into intimate touch with a huge active biomass, whiles the effluent remains relatively free of biological solids. The ABR also does an incredible job in separation acidogenesis and methanogenesis longitudinally down the digester and makes the system more stable (Bassuney *et al.*, 2015).

2.5.1.2 Anaerobic Contact Reactors

Effluents with a high rate of suspended solids are usually treated easily in an anaerobic contact reactor (ACR). Two main components in this reactor design are an agitated digester and a solid settling tank for recycling of micro-organisms. The settled sludge is held into the main digester in the settling tank. The degree of contact and substrate retention time between the microorganism communities and influent substrate are the basic parameters that affect the operation of this reactor type

(Lindmark *et al.*, 2014). ACR has a bigger advantage over conventional anaerobic digesters such (UASB) reactors, in terms of mass transfer rate. Advantages of this system include; less impact of shock loading on the system, favorable pH and limited biomass wash out during the contact process rapidly achieved steady-state times as a result of short hydraulic retention times, mixing, and relatively good effluent quality (Fedailaine *et al.*, 2015). The content of the digester is completely mixed and later separated into a clarifier, and the supernatant is discharged as effluent.

2.5.1.3 Internal Circulation reactors

The Internal Circulation reactor (IC) is an up-flow anaerobic digester made up of essentially two stages. Biogas is collected on sludge bed that is found in the rear of the reactor and moved upwards together with water to the gas-liquid separator found on the upper part of the digester. The wastewater returns to the floor of the reactor due to gravity. Sedimentation of the organic material and the potential reduction of washout occurs at the second stage, established in the upper portion of the digester. Smaller volumes of biogas start producing in this part of the reactor. Parawira *et al.*, (2004), used IC reactor in the treatment of brewery and potato liquid waste. They compared the characteristic of granules in a UASB reactor with that of the IC reactor. This IC reactor device, nevertheless, uses a hybrid of the precepts of the UASB and EGSB digesters (Lindmark *et al.*, 2014).

2.5.1.4 Up-flow Anaerobic Sludge Blanket Reactor

Up-flow Anaerobic Sludge Blanket (UASB) is an incredible option for the treatment of domestic wastewater which was developed to overcome the inherent shortfalls of the conventional septic tank (Moharram *et al.*, 2016). It has also found wide acceptance on an industrial scale because of the possibility of energy recovery, low sludge production, low hydraulic retention time (HRT) and high solids retention time. The high patronized anaerobic reactor for the treatment of industrial wastewater is the UASB (Aboulfotoh, 2018). The using the UASB include low sludge production, low cost, operational simplicity, and biogas production. Operation and maintenance of the UASB reactor usually require approximately less than 1 % of its capital cost per year (Mamais *et al.*, 2019).

2.5.2 Conventional reactors

2.5.2.1 Anaerobic plug flow reactor

Anaerobic Plug flow Reactors (APFR) are mostly adiabatically or non-isothermally operated. The brain behind APFR is that the volume of substrate entering the reactor is the same as the volume of digestate leaving the digester. It is expected by researchers that, the substrate of a APFR must be appreciably thick to prevent particles from settling to the bottom (Burghate 2013). The feedstock moves through the digester as a plug because very little mixing occurs hence the name "plug flow''. APFR does not require mechanical mixing. Total solids (TS) content of feedstock should be in the range of 10 % - 15 %. APFR are usually five times longer than they are wide. Usually, the retention period is 15 to 20 days (Aboulfotoh, 2012). Characteristics of ideal plug flow are considered to have a uniform cross-section concentration. No axial mixing is required (Steele, 2005).

2.5.2.2 Continuous stirred tank reactors

The first generation high-rate anaerobic digester that existed before the inception of other high rate digesters is the continuous stirred tank reactor (CSTR). It is popular in the AD fermentation process for its reliability and its potential to treat liquid waste containing high levels of suspended solids particularly high-strength liquid animal waste and organic industrial effluents. In practice, CSTR is simple to use and more profitable as compared to APFR (Mao et al., 2015). Complete mixing takes place in an ideal CSTR, the feedstock is completely stirred to ensure uniform properties throughout the digester. In reality, no digester would satisfy any of the ideal situations and might incorporate elements of PFR (Dustin and Hansen, 2019). CSTR is often recognized because of the following features: a) Inlet concentration is not the same as the outlet concentration, b) the reaction takes place in the entire reactor volume because of the perfect mixing and c) it also prevents the formation of stagnant zones. The specific retention time distribution is the arithmetic mean of the retention time of all particles (Wirtz and Dague, 1997).

2.5.2.3 Anaerobic sequencing batch reactor

The Anaerobic Sequencing Batch Reactor (ASBR) is a single vessel batch anaerobic digestion reactor developed and patented at Iowa State University (Wirtz and Dague, 1997). A batch reactor is characterized such that there is neither continuous flow of wastewater entering nor leaving the reactor. The system operates in four cycles (thus flow enters, is treated, settled, discharged and the cycle repeats), the content is completely mixed (Wei, 2007). High rates of substrate conversion and biomass flocculation occur as a result of the exposure of microorganisms in an ASBR to variable feedstock concentrations over the duration of the cycle. The cycles must be as frequent to complete the four-stage reaction. The solids residence time becomes independent of the hydraulic retention time when the operation is done in batches without recourse to a settling tank, since the reactor functions as a decanter whenever the stirring mechanism is turned off (Kannan and Singaram, 2015).

2.5.3 Anaerobic membrane reactors

2.5.3.1 Anaerobic filter

The anaerobic filter (AF) is used as the first treatment unit for biogas septic tanks, ABR and biogas settlers having liquid waste with a low content of suspended solids and a narrow COD/BOD ratio. AF has a supporting material layer which supports the development of biofilms on its surface. In the treatment of concentrated liquid waste and wastewaters with low organic load, the AF is the most preferred option. The Anaerobic Filter operates in three ways. It could be in either up-flow or down-flow or combined. There should be a minimum of at least four chambers when one wants to design an AF. The up-flow mode is however preferred because the risk of fixed biomass washed out is reduced (Mang and Zif, 2014).

2.5.3.2 Expanded granular sludge bed reactors

An expanded granular sludge bed (EGSB) digester mimics the design concept of the UASB (Wirtz and Dague, 1997). The EGSB digesters perform best in the treatment of low strength wastewater (ethanol and volatile fatty acid-containing wastewater) with COD range of 0.7 g - 0.9 g (Xi-quan, 2008). The uniqueness of this digester is that a faster rate of upward-flow velocity is designed for the liquid waste going through the sludge bed. To achieve an increment in the flow velocity, tall digesters should be utilized, or effluent recycling should be incorporated or both. The EGSB design is good for low strength soluble wastewaters (less than 1 to 2 g soluble COD/l) or for wastewaters that contain inert or poorly biodegradable suspended particles which cannot be permitted to accumulate in the sludge bed (Wei, 2007)

2.5.3.3 Anaerobic Fluidized Bed Reactor

Anaerobic treatment of different high-strength wastewaters requires very feasible configurations such as the AFBR configuration. The system operates at significantly reduced HRT due to the use of small, porous, fluidized media which permits the digester to retain high levels of biomass concentrations. High-surface-area media should not be used in an AFBR to avoid operating problems such as bed clogging and high-pressure drop (Montalvo *et al.*, 2014). ARBR is a process which has stood the test of time is now widely applied in many industrial applications. The discouraging sides of the system include the pumping power needed to operate the fluidized bed, the high cost of digester packing, controlling the packing level and wasting with bio growth and the possible duration of starting time (Burghate and Ingole, 2013).

2.6 Classification of Anaerobic Digesters based on Mode of Feeding

One of the fundamental ways of distinguishing one digester from the other is the way it is fed and how its effluent is removed. All digesters, either low-technology or high-technology fall under one of these classifications.

2.6.1 Fed-Batch digesters

In batch-fed digesters, the digesters are filled with fresh substrates, usually with a starter and allowed to digest for fixed retention time and then completely removed after the gas has been collected (Sasse, 1988; Al Seadi *et al.*, 2008; Fulford K, 2008). Batch reactors function similar to a landfill, but at higher temperatures and with continuous leachate recirculation, the biogas yield is between 50 % and 100 % higher than in landfills (Holmqvist, 2004 cited by Verma, 2002). The advantage of batch-type digesters is that the substrate can contain lignin and other indigestible matter, as it does not have to be fed through inlet and outlet pipes. Another advantage of this type of digesters is its ability to digest high solids (20 % to 40 % TS) content substrates making it suitable to be operated as a dry digester. Thirdly, it does not require stirring as in the case of wet digestion (Sasse, 1988; Fulford K, 2008; Al Seadi *et al.*, 2008). Batch digesters are further put into three types namely: Single-stage batch system, Sequential batch system and the Hybrid-Up flow Anaerobic Sludge Blanket (UASB). The three types are shown in Figure 2.3.

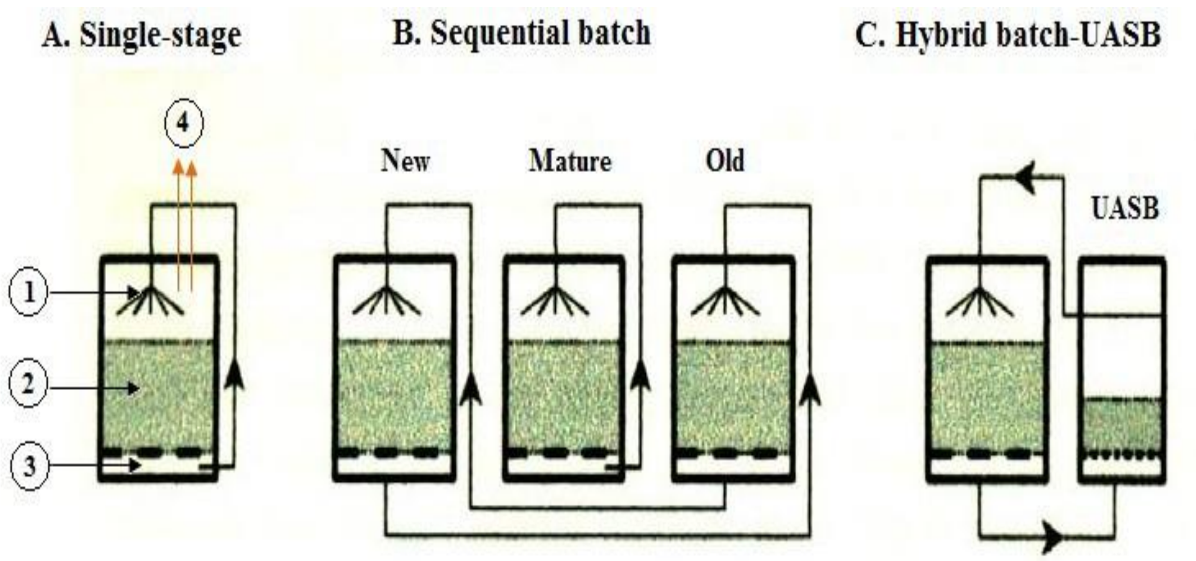

Figure2.3: Types of batch digesters. 1. Leachate sprinkled over the substrate; 2. substrate (20 % -40 % ts); 3. Leachate from a digested substrate; 4. Biogas

2.6.2 Continuous digesters

In continuous-type digesters, the substrate is constantly fed (for example, daily) into the digester once it has been started (Al Seadi *et al.*, 2008). Continuous-fed digesters have inlet and outlet where substrates enter the digester and spent slurries leave the digester respectively in the continuum so far as feeding is done. The inlet and outlet of the digester arranged it such that the spent slurry overflows into a pond as new slurry is added (Abdelgadir *et al.*, 2014). The movement of the slurry through the digester can be achieved either mechanically or by the pressure of the newly fed substrate, pushing out the digested material; this phenomenon is known as the *Displacement Principle*. Unlike batch-type digester, once the digestion process has stabilized, the gas production rate is fairly constant (with constant feed rate and temperature) and predictable (Wirtz and Dague, 1997). Most simple digesters like the balloon plant, fixed-dome plants, and the floating-drum plants are the continuous-feed types. Currently, most of the digesters (both Low-Technology and High-Technology) available in Ghana, Europe, and other parts are continuous-feed digesters.

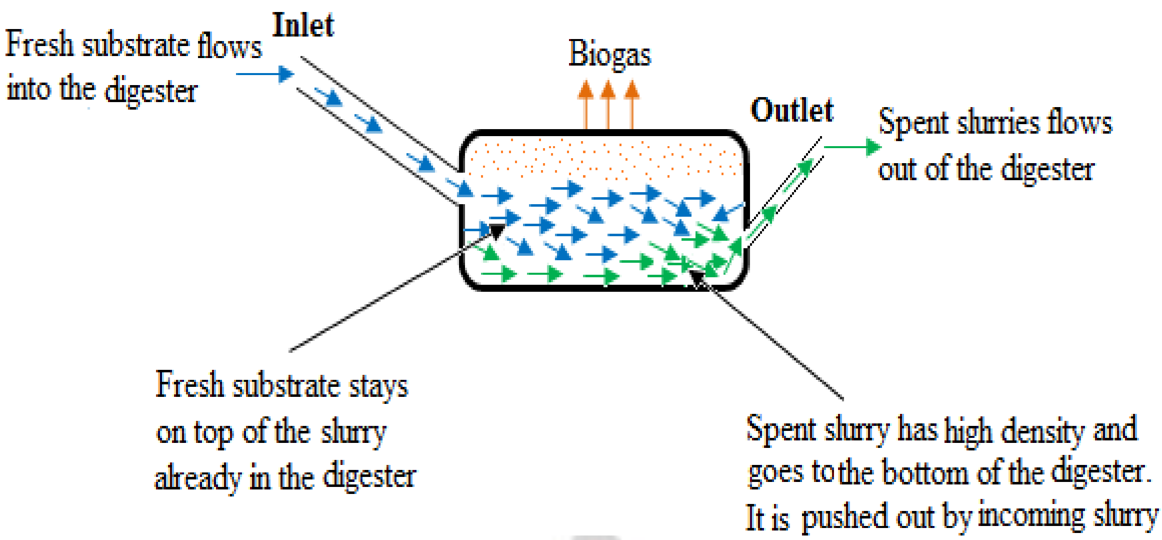

Figure 2.4: Theoretical presentation of the displacement principle employed by the continuous-feed digester

2.6.3 Semi-Batch digesters

Semi-batch digesters are those that are started as batch digesters and also fed regularly. This type of digester is suitable for the co-digestion of straw and dung. Many digesters in China are run in a semi-batch mode (Sasse, 1988). The digesters are filled with vegetable matter, such as straw and garden wastes, and animal dung and a starter. In addition to the existing substrate, the digesters are fed daily with dung (usually from pig and attached latrine) and vegetable wastes. Gas production remains fairly constant due to the quick degradation of more digestible substrates and enhanced by the slow degrading substrates (Wei, 2007). These digesters are emptied once or twice every year with the absence of gas during the emptying and restarting period, is the main disadvantage.

2.7 Classification by type of Substrate fed in the Digesters

The substrates digested in anaerobic digestion systems can be grouped into three main categories on the basis of their total solids (TS) content. Under this category, the digesters are grouped into Wet (Low Solids) and Dry (High Solids) digesters (Verma, 2002)

2.7.1 Wet or low-solids digesters

The low solids (Wet) AD systems are suitable for digesting substrates with a total solids content less than 12% (Amenorfe, 2013). Some of the digesters of this type are the ABR, CSTR Cheng *et al.*(2018) and most of the anaerobic digestion systems employed in wastewater treatment. Others include simple anaerobic systems like the balloon digesters, fixed-dome plants, and floating-drum plants. Generally, the retention time is 14-28 days for high-tech digesters depending on the kind of feed and operating temperature Verma, (2002) or more in the case of simple digesters. The low total solids content of the substrates increases the design volume of the digesters leading to high construction cost. It also promotes non-homogeneity in the reacting mass leading to the formation of a layer of heavier fractions at the bottom of the reactor and floating scum at the top. The bottom layer can damage the propellers while the top layer hinders effective mixing in digesters using mechanical mixers. Another flaw is the short-circuiting, that is a fraction of the feed passes through the reactor at a shorter retention time than the average retention time of the total feed. These (scum and the short-circuiting) lower the biogas yield and impairs the effective treatment of the wastes .

2.7.2 Dry or high solids digesters

These digesters are suitable for digesting substrates with total solids content between 20 % to 40 % (Amenorfe, 2013). The HS systems can handle the impurities such as stones, glass or wood that need not be removed as in LS systems. Contrary to the complete mixing prevailing in LS, the HS is plug-flow reactors hence require no mechanical device within the reactor (Vögeli *et al.,* 2014 cited by Verma, 2007). Dry digesters exhibit higher organic loading rates (15 kg VS/m^3 per day) with a high biogas yield, as compared to wet digesters which have about 6 kg VS/m^3 per day. Also, dry digesters make use of very little water if any thus saving the amount of water used in mixing the slurry (Waltenberger and Kirchmayr, 2013).

2.8 Classification based on operating temperature

Based on the operating temperature of the digester, it may be a mesophilic or thermophilic plant. High-tech digesters are further grouped into Single-stage digesters and Multi-stage digesters according to their complexity.

2.8.1 Mesophilic and thermophilic digesters

Mesophilic digesters are those in which the anaerobic digestion process takes place optimally around 30 to 38 °C or at ambient temperatures between 20 and 45 °C (Galway, 2012). The mesophilic digestion process is done by a large diversity of mesophilic bacteria which are more tolerant to process temperature fluctuations thus making the process more stable and robust. Heating systems may not be installed in mesophilic plants when they are installed in tropical areas. Thermophilic plants, on the other hand, operate optimally in the temperature ranges of 49 to 57°C, or at elevated temperatures up to 70°C, where thermophiles are the primary microorganisms present (Connelly, 2016). Heating systems are installed in these plants to provide the thermophilic temperature level required in the digester. Thermophilic digestion systems are considered to be less stable and require a higher energy input than mesophilic plants. This notwithstanding, more energy is removed from the organic matter (Abdelgadir *et al.*, 2014). This is because the increased temperatures facilitate faster reaction rates and, hence, faster gas yields. Additionally, operating at higher temperatures facilitates greater sterilization of the end digestate. However, the high energy input that is made in order to achieve the higher temperature levels, which may not be outweighed by the energy output of the systems is a setback to the operation of thermophilic digestion systems.

2.8.2 Single-stage digesters

In a single-stage (one-stage) digestion system, all of the sub-processor biological reactions occur within a single, sealed reactor or holding tank. Using a single-stage reduces construction costs, but results in less control of the reactions occurring within the system (Abdelgadir *et al.*, 2014). Since all the bacteria involved in the sub-processes are in the same digester, the inactiveness or over-activeness of one group of bacteria affect the activities of other bacteria. For example, extra acid produced by the acidogenic bacteria reduces the pH in digester thus impeding the activity of the methanogenic bacteria thus affecting the biogas production by the digester.

2.8.3 Multi-stage digesters

Multi-stage anaerobic digestion system consists of two or more digesters arranged such that the sub-processes occur in different separate reactors. Typically, two reactors are used, such that hydrolysis, acidogenesis, and acetogenesis occur within the first reaction vessel while methanogenesis occurs in the second (Verma, 2002). According to Verma, (2002) hydrolysis of cellulose is the rate-limiting factor in the first reactor. However, in the second, it is the rate of microbial growth. For the purposes of attaining uniform temperature gradient and save the bacteria consortia from sudden temperature fluctuation, the substrate (organic waste material) is heated to the required operational temperature (either mesophilic or thermophilic) before being pumped into a methanogenic reactor (Ryan *et al.*, 2010).

Even though this system requires the construction of two digesters thus increasing its construction cost, it has some advantages over the single-stage digestion system. Firstly, in the multi-stages digesters, the rate of hydrolysis and methanogenesis can be controlled (and optimized) making it possible to control the anaerobic digestion process. For example, microaerophilic conditions, which can be provided by supplying a small amount of oxygen in an anaerobic zone, can be used to increase the rate of hydrolysis. Secondly, the system provides greater biological stability for very rapidly degradable wastes like fruits and vegetables (De Mes *et al.*, 2003). This is because, with such substrates, the slower metabolism of methanogens relative to acidogenesis would lead to process inhibition in single-stage digesters (Monnet, 2003). In spite of all these advantages since it is not possible to completely isolate the different reaction phases; some biogas is often produced in the first digester (Burnett and Togna, 2007).

2.9 Attainable region theory

The attainable region (AR) approach is a powerful research technique that has been applied to the optimization of reactor networks (Metzger, 2007). It is also a powerful teaching tool that focuses on the fundamental processes involved in a system, rather than the unit operations themselves. The generic approach to complex reactor design and optimization is to build on previous experience and knowledge to test a new reactor configuration against the previous champion that yielded the best result (Metzger *et al.*, 2007). If a new maximum is achieved, the reactor configuration and process settings are kept. If not, the previous solution is retained and the entire process is repeated. The biggest issue with this trial and error approach is the time it takes. Horn, (1965) defines the AR as the region in the stoichiometric subspace that could be reached by any possible reactor system.

Furthermore, if any point in this subspace was used as the feed to another system of reactors, the output from this system would also exist within the same AR (Metzger *et al.*, 2007). This framework approaches reactor design and optimization in a simpler, easier, and a more robust manner. It offers a systematic *a priori* approach to determining the ideal reactor configuration based upon identifying all possible output concentrations from all possible reactor configurations. One of its advantages over previous approaches is the elimination of laborious and counterproductive trial and error calculations (Peschel, 2010). The focus is on determining all possible outlet concentrations, regardless of the reactor configuration, rather than on examining a single concentration from a single reactor. Approaching the problem from this direction ensures that all reactor systems are included in the analysis, removing the reliance on the user's imagination to create reactor structures (Hildebrandt, 1994). Finally, this general tool can be applied to any problem whose basic operation can be broken down into fundamental processes, including isothermal and non-isothermal reactor network synthesis Neba *et al.*, (2019), optimal control, combined reaction and separation and others. Process synthesis and design usefulness are aided greatly by this alternative approach (Scott *et al.*, 2013).

2.10 Feasibility assessment tool (Scenario Planning)

The feasibility Assessment tool is a strategic planning technique used by institutions to develop flexible long-term Plans (Lohri and Zurbrügg, 2013). The tool entails feature that is not easy to formalize such as shifts in values. Subjective interpretations of facts, new regulations, or new technologies. The scenarios mostly comprise of plausible, unpredicted important circumstances and problems that already exist in some small form in the present day (Spaniol and Rowland, 2018). It is important to select informational features that are both likely and uncomfortable so that decision-makers can predict hidden shortfalls and inflexibilities in structures, procedures, and methods. Hence its application in the selection of a digester. The tool thus assisted in conducting a comprehensive, participatory feasibility assessment of AD technologies for organic waste in developing countries. It examined the technologies, their material chains, stakeholder motivation, interest, and influence, and systematically examines the enabling environment in which the project will be embedded (Cherepovitsyn and Ilinova, 2018).

2.11 Multicriteria Criteria Decision Analysis (MCDA)

The main objective for the use of this technique is to deal with a lot of challenges that human decision-makers when dealing with large amounts of complex information in a consistent way (Pavić and Novoselac, 2016). MCDA techniques are used in the identification of a single most preferred option, ranking options, shortlisting a small data of options for subsequent detailed appraisal, or to separate the acceptable from unacceptable options. As is clear from a growing literature, there are many MCDA techniques and their number is still rising. (Yazdani *et al.*, 2018). There are several reasons why this is so: those supporting the decision may have different analytical skills, their various kinds of decisions which fit the bigger picture of MCDA, the amount or nature of data available to support the analysis may vary, the time required to undertake the analysis may vary, and the administrative culture and requirements of organizations also vary. The purpose of this research has made it irrelevant to review the literature on TOPSIS, AHP, FUZZY LOGIC, VIKOR and COPRA which are some powerful techniques.

2.11.1 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

Hwang and Yoon (1995) were the first people to present TOPSIS, for solving MCDA problems based on the concept that the highest-ranked alternative has the shortest Euclidian distance from the Positive Ideal Solution (PIS) and the farthest from the Negative Ideal Solution (NIS) (Rahim *et al*., 2018). For example, PIS maximizes the benefit and minimizes the cost, whereas the NIS maximizes the cost and minimizes the benefit (Soufi *et al.*, 2015). It assumes that each criterion requires to be maximized or minimized. TOPSIS is an accurate and delightful technique for ranking different likely alternatives, according to closeness to the ideal solution (Srikrishna *et al*., 2014).

2.11.2 Analytical Hierarchy Process (AHP)

AHP mostly deals with subjective judgments and intangible attributes (Whitaker and Foundation, 2017). It is important to note that, since some of the criteria could be contrasting, the AHP has been advocated to be used to solve choice problems where alternatives are evaluated with respect to multiple criteria. It is a special tool used to solve MCDM problems (Roszkowska, 2013). In general, the most preferred option cannot be the one which places a higher value on every single criterion, rather the one which achieves the most suitable trade-off among the different criteria. The decision maker's pairwise comparisons of the criteria are obtained after the AHP has generated a weight for each evaluation criterion. The higher the weight, the more important the corresponding criterion. Scores are assigned to each option according to the decision maker's pairwise comparisons of the options based on that criterion by the AHP. The performance of the considered criterion is dependent on the highest score. Finally, the AHP combines the criteria weights and the option scores, thus determining a global score for each option, and a consequent ranking. The global score for a given option is a weighted sum of the scores is obtained with respect to all the criteria (Whitaker and Foundation, 2017).

2.11.3 Multi-Criteria Optimization and Compromise Solution (VIKOR)

The VIKOR method was discovered to be used for multi-criteria optimization in complex systems. After identifying the material selection attributes and creating a shortlist of materials in a given engineering application, the VIKOR can be used to rank and select the optimum material (Shemshadi *et al.*, 2011). It focuses on ranking and selecting from the alternatives with conflicting and different units criteria (Mardani *et al.*, 2016). In VIKOR approach, the compromise ranking is performed by comparing the measure of closeness to the ideal alternative, and compromise means an agreement established by mutual concessions (Jahan *et al.*, 2011). The VIKOR method determines a compromise solution with non-commensurable and contradicting criteria, including economic, environmental and social criteria. It focuses on selecting and ranking of a set of alternatives and determines compromise solutions for a problem with conflicting criteria, which can help the decision-makers to reach a final decision.

2.11.4 Complex Proportional Assessment (COPRA)

The complex proportional assessment (COPRAS) method assumes direct and proportional dependences of the significance and utility degree of the available alternatives under the presence of mutually conflicting criteria (Stefano *et al.*, 2015). It also considers the output of the alternatives with regards to various criteria and also the corresponding criteria weights. This method opts for the best decision by considering both the ideal and the ideal-worst solutions. COPRAS has the tendency to account for both positive (beneficial) and negative (non-beneficial) criteria, which can be assessed differently within the evaluation stage (Roszkowska, 2015). The most important element that makes COPRAS method superior to other methods is that it can be used to calculate the utility degree of alternatives, indicating the extent to which one alternative is better or worse than other alternatives taken for comparison.

2.12 Fuzzy logic

Applications of this theory can be found, for example, in artificial intelligence, computer science, medicine, control engineering, decision theory, expert systems, logic, management science, operations research, pattern recognition, and robotics. Mathematical developments have advanced to a very high standard and are still forthcoming today (Krejčí, 2018). ‘The notion of a fuzzy set provides a convenient point of departure for the construction of a conceptual framework which parallels in many respects the framework used in the case of ordinary sets, but is more general than the latter and, potentially, may prove to have a much wider scope of applicability, particularly in the fields of pattern classification and information processing (Ojha, *et al.,* 2007). Essentially, such a framework provides a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria of class membership rather than the presence of random variables'.7 'Imprecision' here is meant in the sense of vagueness rather than the lack of knowledge about the value of a parameter (as intolerance analysis).

A fuzzy set theory provides a strict mathematical framework (there is nothing fuzzy about fuzzy set theory!) in which vague conceptual phenomena can be precisely and rigorously studied. It can also be considered as a modeling language, well suited for situations in which fuzzy relations, criteria, and phenomena exist. A fuzzy set is made up of membership functions that embody the degrees of membership with real numbers is [0, 1] interval. If the element has no membership and total membership, the value would be zero and one, respectively, otherwise, if the value is a number between zero and one, it means that the element has a certain degree of membership (Zadeh, 1965). On the other hand, converting the linguistic terms into fuzzy numbers seems a great way to overcome the vagueness and ambiguities. It is very difficult to make decisions in a vague and uncertain environment. For one, sometimes evaluations done by experts based on their experiences are proposed by linguistic variables (Bustince, 2018). To tackle this vagueness and uncertainty, fuzzy theory proposed by Zadeh, (1965) can be applied.

2.13 Linguistic variables in fuzzy logic

One of the fundamental tenets of modern science is that a phenomenon cannot be claimed to be well understood until it can be characterized in quantitative terms today (Krejčí, 2018). Viewed in this perspective, much of what constitutes the core of scientific knowledge may be regarded as a reservoir of concepts and techniques which can be drawn upon to construct mathematical models of various types of systems and thereby yield quantitative information concerning their behavior (Zadeh, 1975). Any variable that represents its data in a linguistics form is called a linguistic variable. The concept of linguistic variable is very complex situations presents itself in decision making or too disorganized to be rationally captured in the usual quantitative form.

2.14 Application of MCDA to waste treatment

For over several decades, waste management problems have been addressed through the use of MCDA techniques. This typically involves the integration of environmental, political, social, cultural, and economic values alongside the preferences of stakeholders while considering the challenges of monetizing essentially non-monetary factors (Kamali *et al.*, 2019 ; Matheri *et al.*, 2016). A number of applications of MCDA techniques to waste management have been presented recently in literature by Suganthi, Iniyan and Samuel (2015), Kamali *et al (*2019) and Wang *et al* (2018). Most of these studies start with reasonable decision-making concerning the selection of anaerobic digester technology by considering a broad range of impacts, operation conditions, environmental, economic, land use and resource use, reuse, and recycling. Although MCDA is a structured approach (Lohri *et al.,* 2013), it is flexible enough to allow the use of value judgment and quite suitable for problems where monetary estimates are not available. In most case according to Suganthi *et al*., (2015), it enables a more practical representation of the decision problem selected, and particularly for the tradeoffs to be made (Pires *et al.*, 2011).

CHAPTER THREE

MATERIALS AND METHODS

This chapter presents the materials and methods used to perform the anaerobic treatability studies, select the PFRs to be used in the optimal digester structure and the application of attainable region technique to the experimental data of the cumulative biogas yield for the scenarios. The substrates used for this experiment were food waste, pineapple waste, abattoir waste, and pig manure. The laboratory experiment was conducted in 5-liter capacity biodigester to determine the cumulative biogas yield of the various substrates, followed by optimization of the bio digester using attainable region technique and lastly the selection of the preferred plug flow digesters using MCDA tool respectively.

3.1 Work flow of study

The flow chart below describes the stages of the research work.

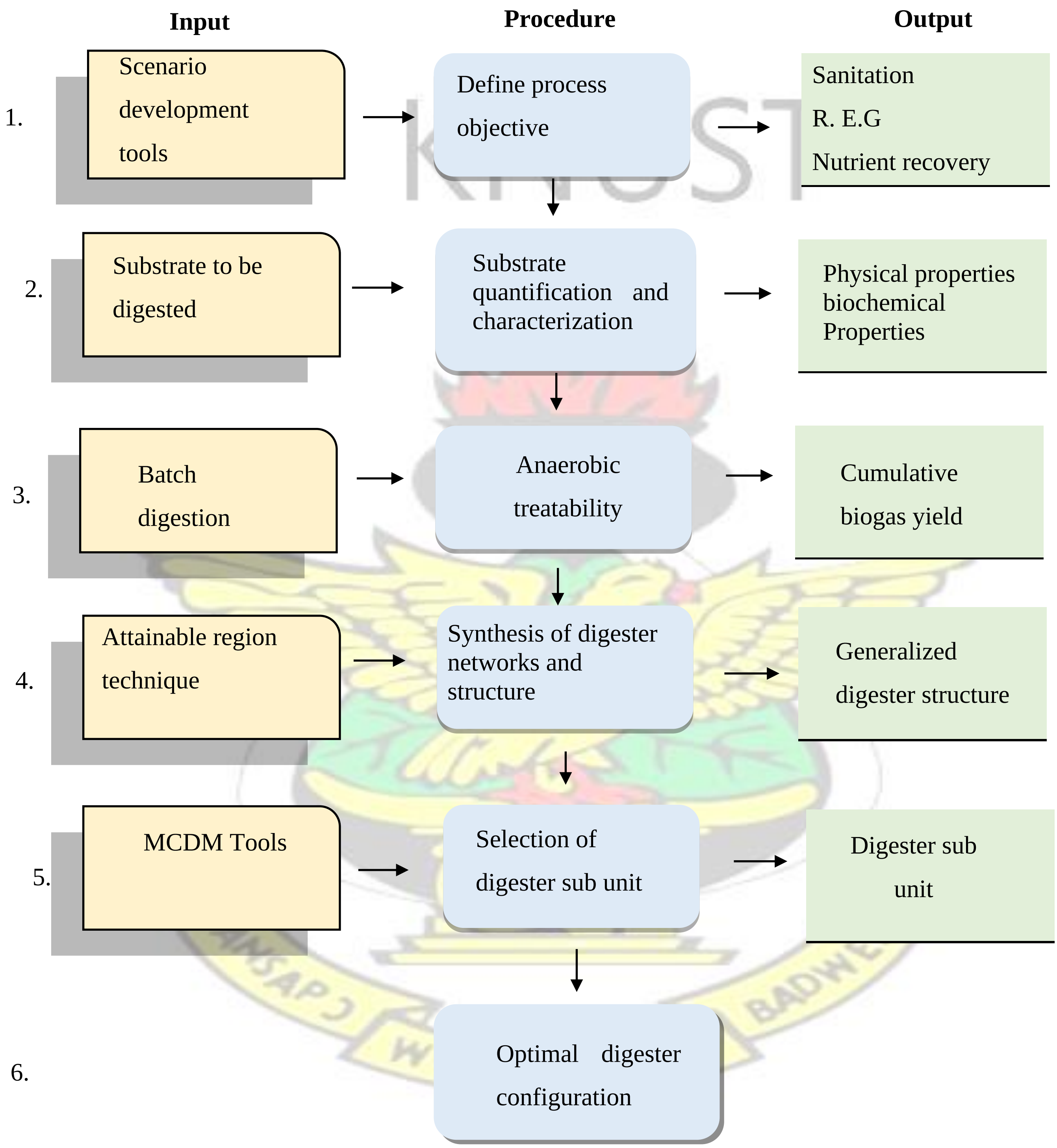

Figure 3.1: Work flow of study

3.2 Theoritic basis of scenario planning

Theoretic basics of scenario planning are possible variants of the future development of events and innovations. Under scenario planning, Kahn (1967) has mentioned the dynamics of qualitative indicators and used the retrospective approach to the functioning and developing the systems. This is how scenarios move from a hypothesis to facts. Thus, according to Kahn (1967), scenarios are a hypothetic succession of events used to study causal relationships and resulting in taking strategic decisions. It is important to consider that it is necessary to base the scenario on many objective factors the decision makers cannot influence (Bretsman, 2011). Scenario planning includes not only the formation of scenarios but also a complex of management solutions, actions and measures within strategic planning (Lindgren 2011; Frolova et al., 2017; Bashmakov *et al*., 2015). According to Kahn (1976), a general strategic long-term tendency that describes the development of the external environment is an important notion in scenario planning. The extrapolation of tendencies within the logics of "general tendency" causes the development of a scenario. Besides, several variations based on realistic opportunities of the system development, forming strategic alternatives are substantiated. Scenario planning, similarly to traditional planning, starts from defining what can and cannot be forecasted. At the same time the scenario goes beyond the predictability and possibility to form clear areas of actions and models. The task of scenario planning is to understand general tendencies that can form the general structure for the scenarios (Cherepovitsyn and Ilinova, 2018).

3.3 Defining process objective (Scenario Planning)

In the planning phase, theoretical considerations, literature, and document analysis and observations analysis (Lohri, Rodić and Zurbrügg, 2013) led to the development of a draft of the feasibility assessment tool. Literature research comprised topics of anaerobic digestion technologies, sustainable waste management, bioenergy recovery, nutrient recovery from digestate and MCDA. Feasibility Assessment framework was adopted to guide the checklists for literature review on AD projects by researchers Spaniol and Rowland, (2018), which both helped identify relevant issues of the AD process. The resulting power-interest matrix helps identify relevant factors affecting the AD process. The strong focus on scenarios that determine the selection of anaerobic digesters derives from the concept of reflexive engineering. Robbins,

(2007) describes reflexive engineering as a more integrated ethical and system-based approach to development projects, which values communities and the environment in which they are sited as well as the technology. In other words, while ‘traditional engineers’ search for technological solutions in a state of ‘partial ignorance’ about the physical and social environment, ‘reflexive engineers’ work with this environment in a joint effort (Cherepovitsyn and Ilinova, 2018).

3.3.1 Scenario 1: Sustainable Waste Management (Sanitation)

Anaerobic digestion systems specially designed for sanitation purposes ensure environmental benefits, reduction of global warming, less disturbance from insects, air pollution also reduces drastically as well as water pollution, forest vegetation is conserved, eutrophication and acidification also reduce as well through anaerobic digestion means.

3.3.2 Scenario 2: Renewable Energy Generation

The world has now grown to accept the importance and the benefits of renewable energy usage because it addresses the prevailing problems associated with energy security, it also eradicates the potential environmental consequence of conventional fuels, and improves the living conditions of those who used it. In the quest to promote renewable energy technologies, biogas technology can be one of the preferred options because the methane generated from the digestion process can be used to cook with gas stoves, heating and generate electricity.

3.3.3 Scenario 3: Nutrients Recovery (Farm Management)

In the practice of sustainable agriculture, AD contributes to closing the nutrient cycle gap which is part of the goal of sustainable agriculture. The digested sludge is nearly odorless, contains significantly reduced levels of pathogens and nutrients such as nitrogen, phosphorus, and potassium which are can be used as good fertilizer and the organic elements recovered also serves as a soil conditioner and a suitable humus Replenisher

3.4 Establishing the driving Forces in three Scenarios

The above scenarios led to the proposal of a structure along twelve distinct dimensions: as seen in the wheel below. Analysis of these dimensions enables a comprehensive view of the Scenarios to identify options for minimizing negative impacts of operating parameters on the anaerobic digesters while maximizing reactor performance (Zurbrügg et al., 2011). For completeness of the analysis, a dimension of developed drivers was added to the framework, as proposed by Wilson, (2007) and applied by (Scheinberg et al., 2010). This dimension looks at mechanisms or factors that have driven the selection digesters for an anaerobic treatment system in the past and at present. Such information is crucial to understand the prevailing limitations of some anaerobic digesters and determine how best to move forward in developing anaerobic treatment systems. Each of the twelve dimensions answers specific questions and together they build the structure of the feasibility assessment tool on a scenario by scenario basis. These twelve dimensions are fair representations of the key trends, conditions, and procedures that influence the selection of an anaerobic digester. Other relevant drivers that do not impinge greatly upon the digester selection process are not included here. Hopefully, the driving forces presented in the wheel below show good coverage of parameters to consider when anaerobic digester has to be selected.

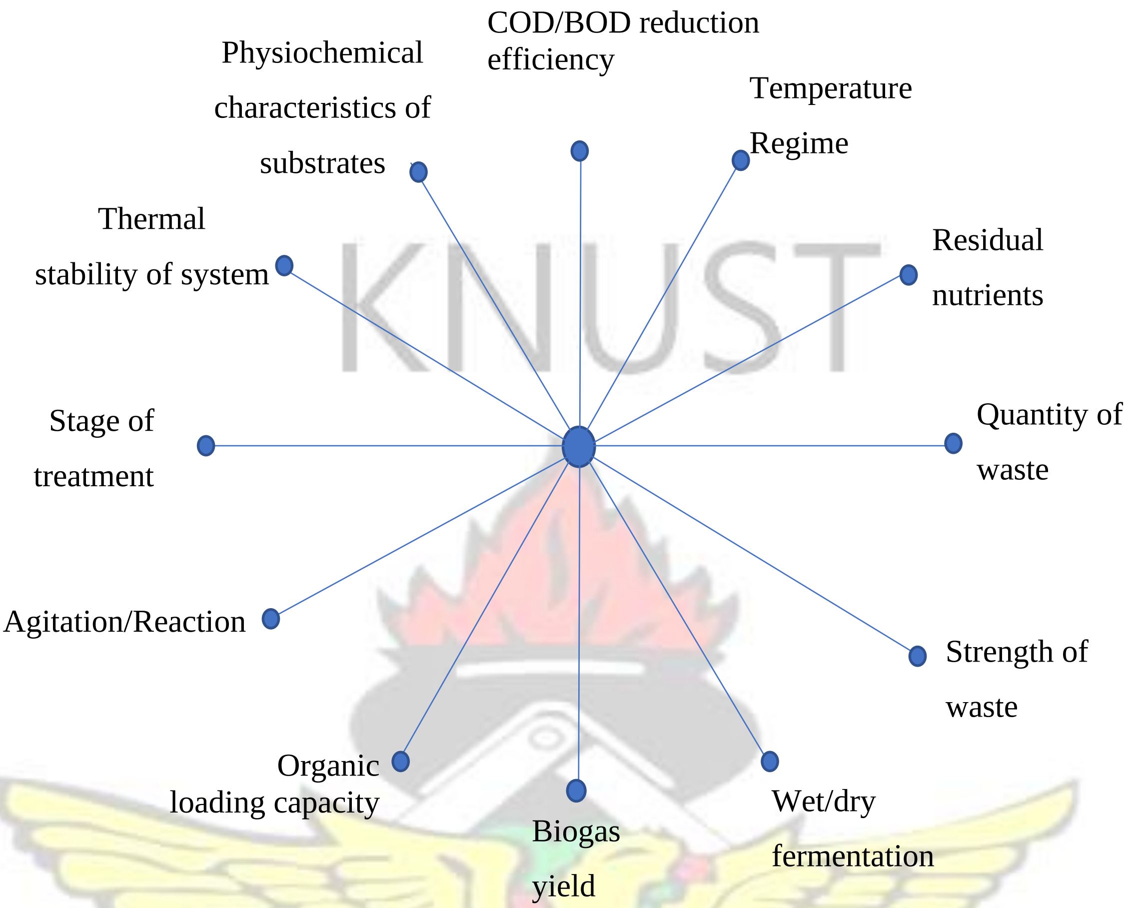

Figure 3.2: Driving forces in the selection of anaerobic digesters

3.5 Defining the driving forces

Development of the drivers related mainly to the twelve factors is discussed below. The ability of a digester to achieve any of the under-listed operational conditions would predict its suitability for a specific scenario.

3.5.1 BOD/VS reduction efficiency of digester

The degree of pollution present in solid wastes and organic sludges; is measured based on VS, whereas for dilute liquid waste, the degree of pollution is expressed in terms of BOD or COD. The ability of an anaerobic digester to treat waste is therefore measured in terms of the percentage reduction in BOD/COD/VS content of the waste. It is important to note that the BOD relates more to the biodegradable fraction of the waste while the COD relates to both the biodegradable and non-biodegradable fraction of the waste.

3.5.2 Temperature regime

Anaerobic digestion can generally be operated in one of these three possible temperature regimes psychrophilic, mesophilic and thermophilic AD each of which has their advantages and disadvantages. The thermophilic regime has a rate-advantage over mesophilic digestion as a result of its faster reaction rates and higher-load bearing capacity and, consequently, exhibits higher productivity compared with mesophilic AD. On the other hand, mesophilic systems offer relatively higher stability compared to thermophilic systems. Ambient/seasonal temperature AD slows biogas production and lower system stability as compared to the mesophilic AD fermentation because of the temperature fluctuations in the surrounding environment. While some are more adapted to specific temperature regimes than others.

3.5.3 Residual Nutrients

The digestive form of anaerobic digestion can be used as biofertilizers or soil amendments. The capability of the digested sludge to create new soil and the replenish humus through supplied organic matter is also guaranteed, when compared to the application of raw slurry on farmlands as fertilizer, This is an asset not found in inorganic fertilizers. Direct determination of biological oxygen demand (BOD) of effluents showed less oxygen demand than in the case of undigested slurry. The likelihood of anoxic soil formation is reduced and oxygen consumption is also reduced.

3.5.4 Quantity of Waste

The quantity of waste to be treated should match up with the digester selected for the treatment process. Some digesters perform better on a small scale than on a large scale. If the digester is to be designed for sanitation then there is no definite amount of waste to be treated to meet the environmental standards, whereas, in renewable energy generation and nutrient requirement of soil, only the quantity of waste corresponding to the energy or nutrient requirement has to be treated.

3.5.5 Wet/Dry Fermentation

Waste by 15-25% low solids are considered wet fermentation; whereas >30% high solids are dry fermentation in the anaerobic digestion process. The dry fermentation process enables the size of the digester to be reduced and it also requires less process water as compared to wet fermentation systems which are well-developed technology but have remarkable problems with the process including larger digester size, requirement of liquid source, and slurry handling problem.

3.5.6 Organic Loading Capacity of the Digester

Organic loading capacity represents the number of volatile solids or organic matter (COD or BOD) fed into a biogas digester per day under continuous operation. The loading rate of anaerobic reactors is limited by the processing capacity of the microorganisms. Anaerobic digester systems can be classified as high rate or low rate depending on whether the solids and hydraulic retention times are coupled or uncoupled. This implies that the greater number of existing high-rate digesters have a built-in mechanism that retains biomass in the digester or to separate bacterial sludge from the outlet and recycled back to the reactor. The increase in solids retention time in high rate systems makes it possible to withstand a higher loading capacity compared to low rate systems. Also, the loading capacity also varies within high rate systems depending on the mechanism employed to uncoupled solids and biomass retention times.

3.5.7 Strength of Waste

Waste produced contains an appreciable fraction of volatile (organic) solids. These volatile solids are fats, carbohydrates, proteins and other equally important nutrients which represents its strength that is used by the anaerobic bacteria as food, energy for the growth and reproduction.

3.5.8 Stage of Treatment

There are basically two-stage treatment processes in Anaerobic Digestion. Primary treatment procedure, this efficiently reduces settleable and digestible solids and organics whereas the Secondary treatment also removes nutrient such as nitrogen, improves hygienisation, and reduces COD and BOD.

3.5.9 Mixing/Reaction (no axial mixing)

Anaerobic digesters can be operated as a mixed or a reacted system. Mixing in Anaerobic Digestion systems provides a homogeneous substrate, prevents stratification and formation of a surface crust. In mixing systems, the SRT is equal to HRT, whiles in the reaction are also limited by problems like low TS concentration with floating and settling layers**.** Abunde e*t al*., (2019) defined mixing reaction as shown in the schematic diagram below Figure 3.3.

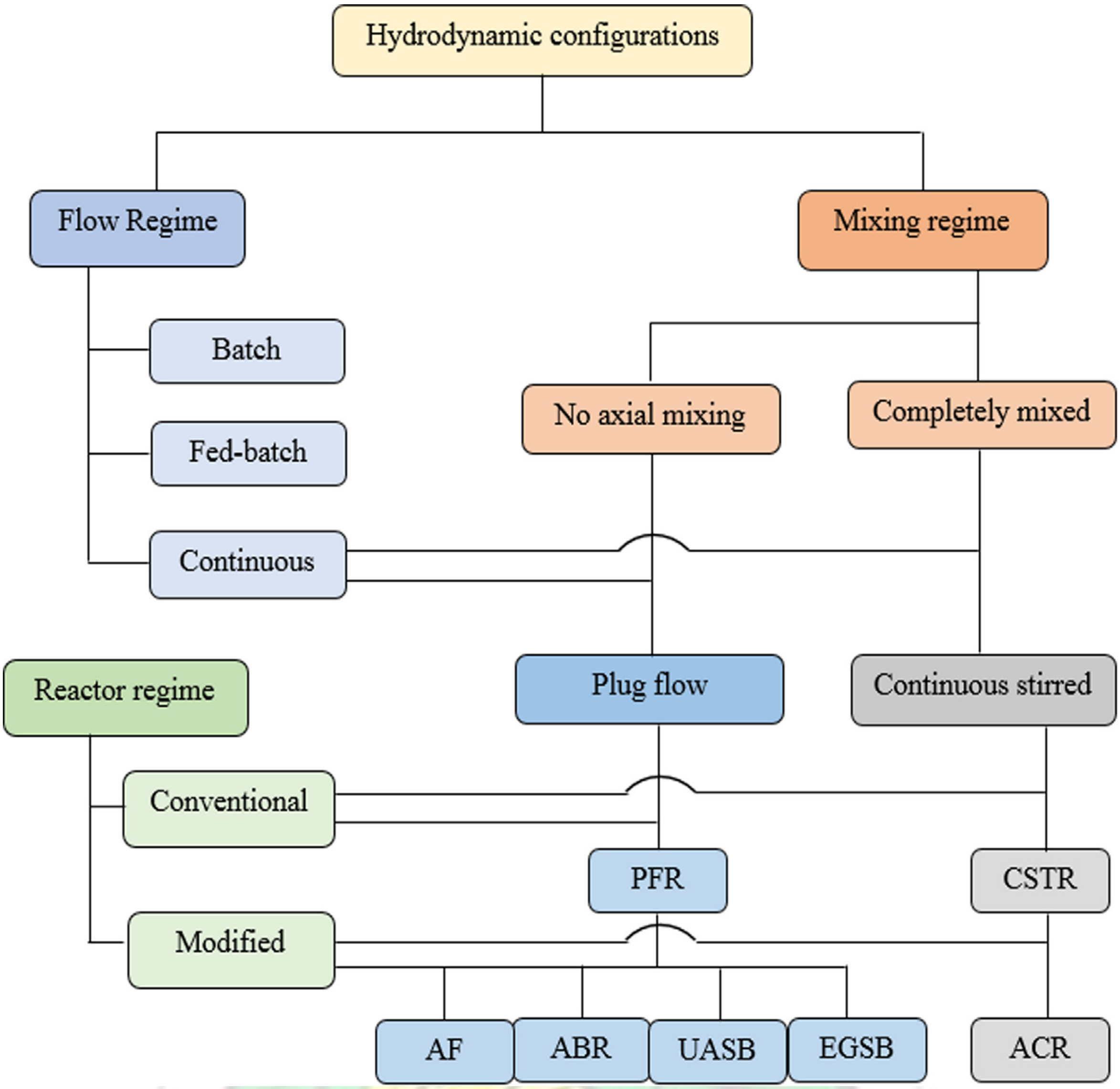

Figure 3.3: Mixing and reaction (no axial mixing) process in anaerobic digesters

Source: Abunde *et al*., (2019).

3.5.10 Biogas Yield of Substrate and Digester

The quantity, quality, and type of substrate available for use in the biogas plant constitute the basic factor of biogas generation. Biogas produced from waste is a mixture of methane, carbon dioxide, water vapor, and a few other gases, notably H_2 and H_2S

3.5.11 Thermal Stability of the system

Temperature is an important parameter in the operation of anaerobic digesters and there exists an optimal temperature at which the system is at its best performance. However, in practice, small scale on-site systems are performed at ambient temperatures. Ambient/seasonal temperature AD demonstrates lower value biogas production and lower system stability of the system than the isothermal (Controlled at constant temperature) process resulting from temperature fluctuations in the surrounding environment. Some digesters are more adapted to withstand temperature variations than others.

3.5.12 Physiochemical Characteristics

There are several important parameters used to monitor anaerobic processes. These include volatile fatty acids, organic dry matter, pH value, C/N ratio, acidity-alkalinity, and substrate structure. The hydrolysis, acidogenesis, and acetogenesis take place in a wide range of pH values, whiles methanogenesis when the pH is neutral. The rate of biogas production is lower when pH values are outside the range of 6.5 - 7.5.

3.6 Identify the casual links between the drivers

Description and ranking of the possible common links between each specific driving force in enlisting forces with the other driving forces as ‘strongly important’, ‘somewhat important’ was done. Literature revealed the possible linkages among the driving forces and scores were assigned to each factor (3, strongly important; 2, important; 1, somewhat: 0, not relevant). From even this crude matrix below, we can draw some tentative conclusions: 1) The links supposedly represent causal relationships (rather than final impacts); this is useful information for the selection process. 2) The scenarios under study usually have their drivers causally linked to all the others, with most of the links viewed as ‘strongly relevant’.

Table 3.1 Identifying casual links.

No.	Critical Dimension	Sanitation	R.E.G	(Nutrients Recovery)
1.	COD/VsReduction Efficiency	3	3	2
2.	Retention of Residual Nutrients	3	0	3
3.	Total Solids content in the Digester	3	3	3
4.	Organic Loading Capacity	3	2	2
5.	Quantity of Waste	1	0	0
6.	Biogas Yield	1	3	1
7.	Wet/Dry Fermentation	1	1	0
8	Thermal Stability of the system	3	2	2
9.	Axial Mixing	3	3	3
19.	Strength of waste	2	1	2
11.	Stage of Treatment (Primary and secondary)	3	3	3
12.	Physio-Chemical Characteristics	1	1	2
12.	Temperature regime of digester	2	0	2

3.7 Developing critical dimensions of stylized scenarios

The critical dimensions of the developed scenarios in this study give a collective, multifaceted space within which the scenarios were mapped. This was done after identifying causal links between the driving forces. The proposed dimensions did not necessarily imply causal assumptions; but rather, they have deduced in terms of the dimensions salience as descriptors of the most critical attributes of the representation of the possible occurrence in the digester selection process.

3.8 Substrate quantification and characterization

3.8.1 Study area

The anaerobic digestion experiment was conducted at the Department of Agriculture and Biosystems Engineering at Kwame Nkrumah University of Science and Technology (KNUST), in the Ashanti Region of Ghana. It is located within 06˚41’5.67” N 01˚34’13.87” W.

3.8.2 Waste collection

Hotel food waste (Substrate one) was collected from the Golden bean hotel located at Ahodwo, pineapple waste (Substrate Two) was collected from the fruit vendors working at Adum, Kumasi abattoir also provided Abattoir Waste (Substrate Three) for the experiment and the pig manure (Substrate Four) was gathered from Zoro pig farm located at Ozoro farm, Atonsu**.** The seed sludge was also collected from a $40m^3$ fixed dome digester at the Kumasi Institute of Tropical Agriculture. Before performing anaerobic digestion test for biogas production, a physicochemical analysis was performed on all these substrates following the protocols described below.

Pig Manure

Pineapple Waste

Abattoir Waste

D Food Waste

Figure 3.4: Substrates used

3.9 Substrate characterization

The following parameters were determined during the characterisation process:

a) Physical characteristics (Total Dissolved Solids, Volatile Solids, Total Solids and moisture)
b) Chemical characteristics (Chemical Oxygen Demand (COD) and Alkalinity)
c) Macro nutrients (Carbon, Nitrogen, Phosphorus and Sulfur)
d) Biochemical composition (Volatile Fatty Acid, protein, Ash)

3.10 Analytical methods and statistical analysis

The total solids (TS) determination was carried out using the gravimetric method (Standard Methods No. 2540 B. Total dry solids at 103 - 105 ° C). 100 ml of the sample placed in the evaporating dish is heated to 320 °C to evaporate all the water, then take to the drying oven until the constant weight remains. The solids fraction was calculated by the difference of the initial weight and final weight. In the case of the volatile solids (VS) determination, the gravimetric method was used (Standard Methods No. 2540 E. Fixed and volatile solids calcination at 550 °C). The sample was incinerated in the muffle at 550 ° C for 15 minutes. The volatile fraction was obtained by weight difference.

The phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) determinations were made in the DR 2800 spectrophotometer, based on the calibration standards, the verification was carried out and the corresponding measurements were made.

The Chemical Oxygen Demand (COD) determination (Standard Methods 5220-D Colorimetric Method Reflux Closed). 50 ml of sample was placed in a 500 ml reflux balloon, and 1 g of mercury sulfate (HgSO4) was added in agitation with 5.0 ml of sulfuric acid. It was mixed with 25 ml of 0.250 N potassium dichromate solution and placed under recirculation, then the remaining sulfuric acid (70 ml) was added through the end of the condenser and the measurement was made. In the meantime, Biological Oxygen Demand (BOD) Determination (Standard Methods 5210 B. 5-Day BOD Test), BOD5 was calculated from the difference between initial and final dissolved oxygen (DO) for 5 days.

3.10.1 Moisture determination

5 g of the sample was weighed into moisture can. The content was then dried at a constant temperature of 105°C in a drying oven to obtain the dry samples.

$$Moisture\ Content\ (\%) = \frac{weigth\ fresh\ sample - weight\ of\ dry\ sample}{Weight\ of\ fresh\ sample}\ x\ 100 \qquad (1)1$$

3.10.2 Nitrogen determination

Laboratory protocol was followed and the Nitrogen present in sample was determined as follows: 2g of the substrate was weighed into a 500ml long-necked Kjeldahl flask. 10ml distilled water was added to moisten sample. One spatula full of a Kjeldahl catalyst mixture of l part Selenium + 10 parts $CuSO_4$ + 100 parts Na_2SO_4 was late added. 20 ml conc. H_2SO_4 was later added and digested until teh solution was clear and colorless. The flask was left to cool and decant fluid into a 100 ml volumetric flask and distilled water was added. An aliquot of 10ml of fluid was transfered by means of a pipette into the Kjeldahl distillation apparatus. 90mls of distilled water was then added to make it up to 100mls in the distillation flask. 20ml of 40% NaOH was dispensed. The distillate was collected over 10ml of 4% Boric acid and three drops of mixed indicator in a 200ml conical flask. Titration was performed by collecting distillate (about 100ml) with 0.1 N HCl till blue color changes to grey and then suddenly flashes to pink. It should, however, be noted that blank determination must necessarily be carried out without the sample. The presence of Nitrogen gave a light blue color. Weight of lg per sample was used, considering the dilution and the aliquot taken for distillation.

Calculation:

$$= \frac{2g\ \times 10ml}{1000} = 0.2g \qquad (2)$$

Thus, the percentage of Nitrogen in the plant sample is,

$$\%\ N = \frac{14 \times\ (A - B)\ \times N \times 100}{1000 \times 2} \qquad (3)$$

Where:

A = volume of standard HCl used in the sample titration

B = volume of standard HCl used in the blank titration

N = Normality of standard HCl

% Crude Protein (CP) = Total Nitrogen (N_T) x 6.25 (Protein factor)

3.10.3 Crude fat determination

The crude fat was determined by weighing 2gof dried sample into an extraction thimble. The thimble was placed inside the Soxhlet apparatus. A dried pre-weighed solvent flask was placed beneath the apparatus and about 200ml of petroleum ether was added and connected to condenser and extracted for 2-3 h. On completion, the thimble was removed and reclaimed using the ether apparatus. The ether was completely removed from the boilt water bath and the flask was dried at 105°C for 30 min. It was then cooled in a desiccator and weighed. Crude Fat (% OF DM) was determined by the formula below.

Calculation:

$$= \frac{weight\ of\ fat}{weight\ of\ sample} X \frac{100}{1} \quad (4)$$

3.10.4 Crude fiber determination

2 g of the fat-free sample was transferred into a digestion flask. 200 ml of hot sulphuric acid was added to it and it was placed into the digestion flask under the condenser. The sample was brought to boil gently for exactly 30 min. The residuw obtained was later transfered back to the digestion flask and 200 ml of hot sodium hydroxide was added to the sample. Th sample was brought to boil withn one minute. After boiling for exactly 30 min, it was filtered through the porous crucible and washed with boiling water and about 15ml 95% alcohol. Sample was dried at a temperature of 105°C until constant weight, it was cooled and weighed. It was later ashed at 550°C for 30min, cooled and weighed. The weight of fiber by difference as shown below.

Calculation**:**

Crude fibre (% of fat-free DM)

$$= \frac{(weight\ of\ crucible\ plus\ dried\ residue) - (weight\ of\ crucible\ + ash\ reduced)}{(weight\ of\ sample)}\ x\ 100$$

(5)

3.10.5 Determination of ash

2 g sample was weighed into a dry, tared porcelain dish and then placed in a muffle furnace at 550°C for 4 h. It was later cooled in a desiccator and weighed again.

Calculation:

$$= \frac{(weight\ of\ ash)}{(weight\ of\ sample)}\ x\ 100 \qquad (6)$$

3.10.6 Carbohydrate determination

The determination of the percentage of total carbohydrate was carried using the values obtained for NFE and crude fiber in the formula below:

% Carbohydrate = % Nitrogen-Free Extract (NFE) + % Fibre (6)

Nitrogen-Free Extract (NFE) represents the non-structural carbohydrates such as starches and sugars and is found by difference. NFE was determined by calculation after the determination of the various components of the proximate analysis using the formula below:

%NFE (on dry matter basis) = 100 – (% CP + % CF + % Ash + % EE) (7)

Where, NFE = nitrogen-free extractDM = dry matter EE = ether extract or crude lipid CP = crude protein CF = crude fiber

3.10.7 Biogas production

Biogas production rate was monitored every day. Even though methane is the final product in AD and its productivity is related with digester's performance, the scope of the study did not consider the composition of the biogas because the experimental data for the total volume of biogas was the only information needed to design the attainable regions of the reactors.

3.11 Treatability studies

Anaerobic batch digestion test was performed in 5 L bottles for a 30day period. The substrate was mixed using a paddle before feeding it into the biodigesters. For each batch 4.5kg of the substrate (effective quantity) and 0.5 kg of inoculum were used. It composed of 1 liter of added water. 0.5L gas collection bag was connected to the bottle using a drip set. Silicon sealant was used to make set up an airtight one. The system was allowed to run for 30 days and digesters were agitated by shaking it every day to avoid the formation of surface crust which prevents contact between microorganisms and the substrate. The water was added because only the solid part of the feedstock dejection was used for the experiments and also to improve the digestion process. The infusion bags connected on the outside of the biodigester as seen in Fig. 3. 5 was monitored and detached three times in a day to determine the volume of gas produced until the gas stopped producing The observation of the total amount of biogas was recorded every day.

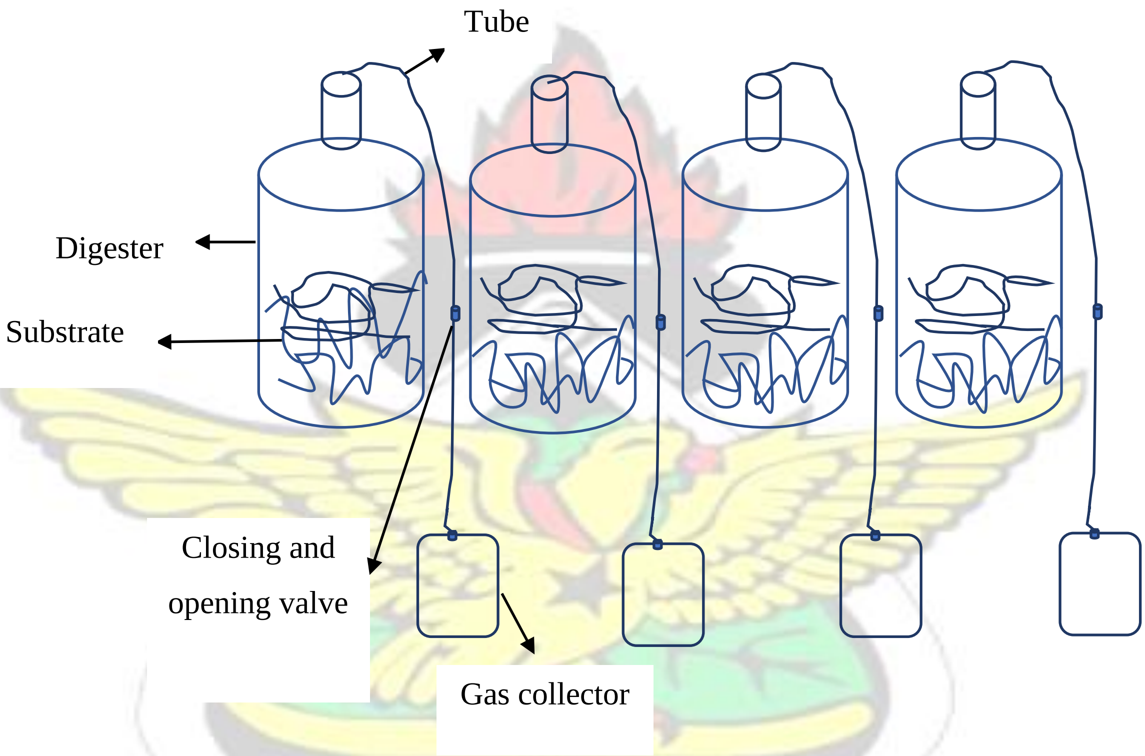

Figure 3.5: Experimental set-up of the cumulative biogas production

Figure 3.6: Monitoring the cumulative biogas production

3.12 Synthesis of digester networks

AR is one of the more recent philosophical ideas which has immensely enriched chemical process (AD) design task. The idea is to keep aside the brute mathematical force used on this concept and convey the simple structural beauty of the profound concept of AR in this study. The Attainable Region (AR) theory was used to incorporate elements of geometry and mathematical optimization, to design and improve the operation of Anaerobic Digesters. It converted the total biogas yield obtained from the cumulative biogas digestion into the possible reaction configurations for the various substrates used.

3.12.2 Construction of attainable regions

The optimization of digestion time using the attainable region technique is done using the following steps:

Step 1: Construction of base trajectory

In AR convention, when dealing with data involving residence time-space it is often conventional to plot residence time vertical axis while concentration or yield is plotted on the horizontal axis. Figure 4 presents the cumulative biogas yield curve plotted in AR convention and the curve ABCD is called the base anaerobic digestion trajectory. A key criterion for selecting variables in AR is that they must obey the linear mixing law. It can be shown that the residence time of a system must fall the straight line between the retention periods, τ_1 and τ_2 comprising the system. This implies the residence time obeys the linear mixing law, Eq. (8)

$$= \lambda\tau_1 + (1 - \lambda)\tau_2 \quad (8)$$

The cumulative biogas yield (y_t) is given by the volume of biogas produced (mL) per mass of substrate added to the digester (g). $y_t = V_g/m_S$. Assume we have two digesters of known biogas yield, we can obtain the actual volume of biogas produced for digesters 1 and 2 by $V_{g1} = y_{t1}m_{S1}$ and $V_{g2} = y_{t2}m_{S2}$ respectively. The total cumulative biogas yield may be determined mass conservation for both digesters. Conservation of biomass sees to it that the sum of the mass of substrate in the mixing chamber is equal to the total value of the individual substrate masses contained in digesters 1 and 2, which is given by $m_{ST} = m_{S1} + m_{S2}$. Computing the biogas yield of the entire system is equivalent to determining the biogas yield for a mixture of digesters 1 and 2 since the density of the liquid phase of the digester can be assumed constant. The biogas yield of the mixture is given by the ratio of the total volume of biogas produced to the total mass of organic substrate added as shown by Eq. (9).

$$y_{tM} = \frac{y_{t1}m_{S1} + y_{t2}m_{S2}}{m_{ST}} \tag{9}$$

If we set $\alpha = m_{S1}/m_{ST}$ then Eq. (33) can be written as Eq. (34), which is similar to the linear mixing law. What this means practically is that if we mix the contents of the liquid phase of two digesters, each of which contains a given mass of organic substrate, then the total cumulative biogas yield of the mixture will lie in a straight line joining that of both digesters.

$$y_{tM} = \alpha y_{t1} + (1 - \alpha)y_{t2} \tag{10}$$

This is known as the lever-arm rule and the process of combining the contents of two parallel digesters of different substrate masses results in a linear mixing law measured in term of cumulative biogas yield.

Step 2: Determine bypass and concavity using a mixing line

I observe that the based anaerobic digestion trajectory is given by curve ABCD, The resultant curve concave in nature with reference to the residence time axis, which may be occupied by connecting points A and C with a mixing/stirring line as shown in Figure 4.6.

Step 3: Further optimization using progressive batch trajectory and the mixing line

3.13 Selection of digesters sub unit

The method for the evaluation of waste treatment alternatives consists of two basic stages: (1) AHP computations to know criteria weights and (2) evaluation of alternatives with

FTOPSIS, where the best results may be expressed as an interval rather than an exact ideal solution. In the first stage, criteria defined for the assessment of the alternatives have been integrated into a decision hierarchy. AHP model is structured such that the objective, criteria, and waste management alternatives are on the first, second, and third-level, respectively. A weighting factor associated with each of the criteria can be derived by AHP throughout a hierarchy process. Pairwise comparison matrices are formed to determine the criteria weights. Computing the geometric mean of the values obtained from the individual evaluation can lead to the identification of the final pairwise comparison matrix.

The weights of the criteria are calculated based on this final comparison matrix. With the aid of the derived weighting factors, the ranking of waste management alternatives can be determined by TOPSIS method in the second stage. Based on the iterative process, different intervals are defined with respect to the distance between linguistic variables that uniquely reflect the possible sources of uncertainty. In such an iterative procedure, it is expected that repeated calculations for testing several intervals that are intimately linked with the major sources of uncertainty. Beginning with an initial guess in regard to which range might be possible to reflect the fluctuations expressed by the interval, and might disturb the determination of a specific solution more close to the ideal solution. A schematic diagram of the proposed method can be seen in Fig. 3. An iteration might be terminated when all types of uncertainty can be fully taken into account.

3.13.1 Analytical Hierarchy Process

Decision-making in the context of the environment is quite complex and multidimensional in nature, in such a way that decisions have to be made in view of diverse spheres of influences. Examples include decisions involving waste recycling and the development of new facilities for waste disposal. Making these decisions could affect diverse domains, from individuals to authorities and organizations, or to society as a whole. The interactive and participatory nature of AHP makes it easier for both the analyst and the decision-maker (who could be a number of groups of stakeholders or consensus experts) to learn more about the problem in detail and make sure that the interests of all the stakeholder groups are represented and taken into consideration. The analysis uses the AHP approach to identify options or alternatives for suitable waste disposal. The AHP helps to break down the problem into small parts with the aim of assisting decision-makers in preference assessment. First, the problem is constructed into a structured hierarchy (Figure 3.7). The top of the hierarchy represents the goal level; the next level is that of criteria and sub-criteria (in some cases), and the lowest level denotes options. Pairwise comparisons permit the analyst to concentrate only on one element at a time: "how strongly important is one criterion related to another with regards to the goal?"

The AHP is developed based on the following five steps (Saaty, 1980):

a) Define the problem, and determine the objective;
b) Development of the hierarchy from the top (the objective from a general viewpoint) through the intermediate levels (attributes and sub-attributes on which subsequent levels depends) to the lowest level (the list of alternatives);
c) Employ simple pair-wise comparison matrices for each of the lower levels;
d) Undertake a consistency test; and
e) Estimate relative weights of the components of each level.

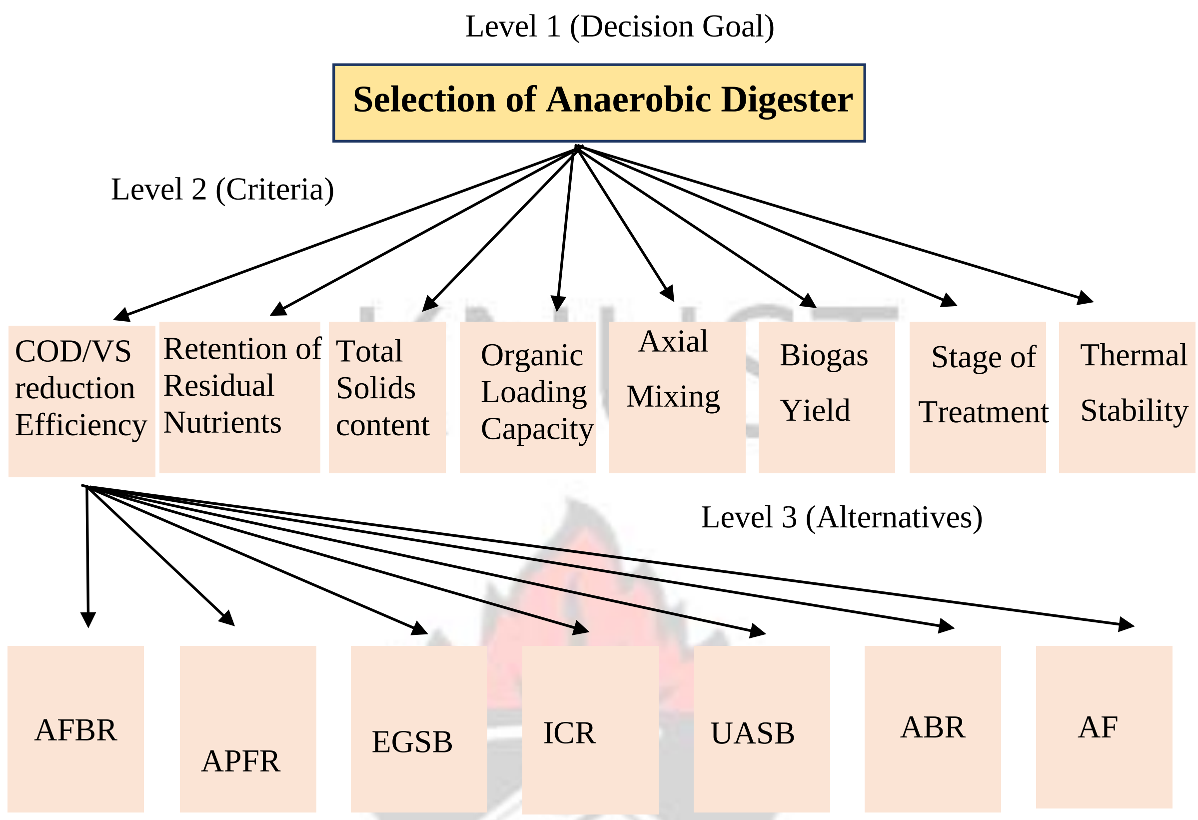

Figure 3.7 Flow of the analytical hierarchy process

3.13.1 Fuzzy logic

Suganthi *et al.*, (2015) have identified optimal strategies in the planning of energy management systems under multiple uncertainties using fuzzy-random interval programming model. The general properties of fuzzy logic, as explained by Zadeh (1965), are as follows: in fuzzy logic, instead of consideration based on exact data, approximate consideration is used. In fuzzy logic, all data are shown as values between 0 and 1. The information in fuzzy logic is verbal, such as "big," "small," "more," or "few." The fuzzy implication process is conducted according to rules that are defined between the verbal expressions. Every logical system can be defined as fuzzy. Fuzzy logic is very suitable for systems whose mathematical models are hard to develop. Fuzzy logic has the ability of processing uncertain or incomplete information and helps in effectively capturing and compressing the data and uncertainties present in energy modelling (Ludwiz, 2016). Guilen, (2016) has used a novel fuzzy based method for assessing the various energy conversion technologies taking into account the environmental aspects and have concluded that renewable energy can utilize this approach for sustainability. Guilen, (2016) have developed a fuzzy based expert system model to determine an unique fuzzy project priority index for prioritizing renewables-to electricity system. The variables consider the life cycle analysis and hence this priority index will be highly useful to practitioners to choose a renewable energy based electricity system. Kyriakarakos *et al.*, (2014) have presented the design and implementation of fuzzy cognitive maps based decision support toolkit for renewable energy systems planning and has tested it in Crete Island. This toolkit will be very useful for decision makers to critically select an appropriate digester for anaerobic digestion. It is found that fuzzy logic is also being used extensively as an assessment/evaluation tool (Kaminaris *et al.*, 2006). When various options are thrown open to policy makers, it becomes imperative to rationally and optimally choose the best resource considering several constraining factors.

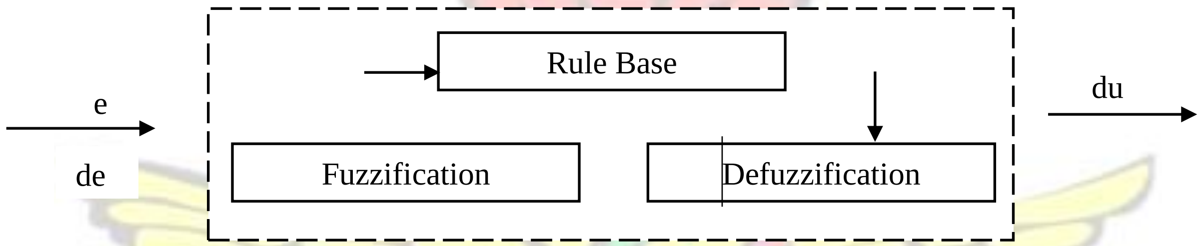

Figure 3.8: Components of fuzzy logic

The Fuzzy Logic system consists of 3 components. These are fuzzification, the rule base, and defuzzification. Fuzzification, the first component of the Fuzzy Logic, converts the exact inputs to fuzzy values. These fuzzy values are sent to the rule-base unit and processed with fuzzy rules, and then these derived fuzzy values are sent to the defuzzification unit. In this unit, the fuzzy results are converted to exact values. The Fuzzy Logic's input values are generally the control error and the variation of this error in one sampling time. According to these variables, a rule table is produced in the Fuzzy Logic's rule-base unit. A Fuzzy set ~A can be defined mathematically by a membership function m~A ðXÞ, which assigns each element x in the universe of discourse X a real number in the interval [0,1]. The membership function for a triangular fuzzy number $\tilde{A}$ can be denoted b

$$\mu_{\widetilde{Ax}} = \begin{Bmatrix} \frac{x-a}{b-a} \\ \frac{c-x}{c-b} \end{Bmatrix} \qquad \begin{matrix} x < a \\ a \le x \le b \\ b \le x \le c \\ x \ge c \end{matrix} \tag{11}$$

Some operational rules such as summation, multiplication, reverse and the distance between two TFN, A = (a_1, a_2, a_3) *and* $B = (b_1, b_2, b_3)$ *are stated as Eq* 2. *to Eq* 5.

$$\breve{A} \oplus \breve{B} = (a_1, a_2, a_3) \oplus (b_1, b_2, b_3) = (a_1 + b_1,\ a_2 + b_2,\ a_3 + b_3) \tag{12}$$

$$\breve{A} \otimes \breve{B} = (a_1, a_2, a_3) \otimes (b_1, b_2, b_3) = (a_1 b_1, a_2 b_2, a_3 b_3) \tag{13}$$

$$\widetilde{A^{-1}} = \left({}^{1}/_{a_1}, {}^{1}/_{a_2}, {}^{1}/_{a_3} \right) \tag{14}$$

$$\text{D}\,(\breve{A}, \breve{B}) = \sqrt{\frac{1}{3}\left[(a_1 - b_1)^2 + (a_2 + b_2)^2 + (a_3 + b_3)^2\right]} \tag{15}$$

3.13.2 TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)

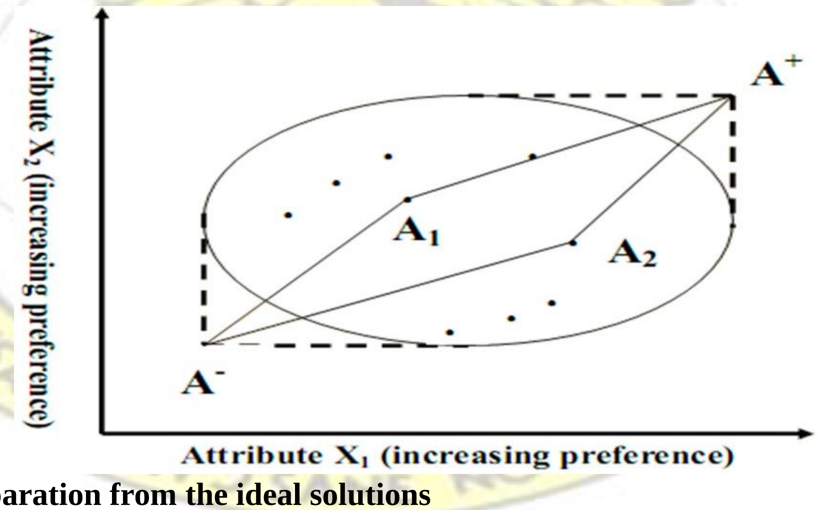

Figure 3.8 Separation from the ideal solutions

TOPSIS is a linear weighting technique which was first proposed in its crisp version. Since then, this method has been widely adopted to solve MCDM problems in many different fields. TOPSIS views an MCDM problem with alternatives as a geometric system and m points in the n-dimensional space. This method is based on the concept that the chosen alternative should have the shortest distance from the positive-ideal solution, and the longest distance from the negative ideal solution. TOPSIS defines an index called similarity to the positive-ideal solution and the remoteness from the negative-ideal solution. Then the method chooses an alternative with the maximum similarity to the positive-ideal solution. The distances may be either summed up in the Euclidean sense or pondered, hence prioritizing one of the two distances. It is often difficult for a decision-maker to assign a precise performance rating to an alternative for the attributes under consideration. The merit of using a Fuzzy approach is to assign the relative importance of the attributes using Fuzzy numbers instead of precise numbers. In this study, the interval values are triangular Fuzzy numbers. To find the middle value of a Fuzzy number, the lower bound and upper bound of the interval data are averaged arithmetically. Fuzzy TOPSIS mathematics concept adapted from Wang and Chang

3.13.2 A hybrid of fuzzy TOPSIS and AHP

In this section, the proposed two-phased approach is for selecting and ranking the Digesters. At first, AHP is used to compute the weights of criteria for anaerobic digesters. Then, the FTOPSIS method is applied to prioritize the optimal digester alternatives according to the mentioned criteria listed above. The AHP method is used to determine the preference weights of each criterion and then Fuzzy TOPSIS technique is used to find out the best prioritize digester among the screened anaerobic digesters.

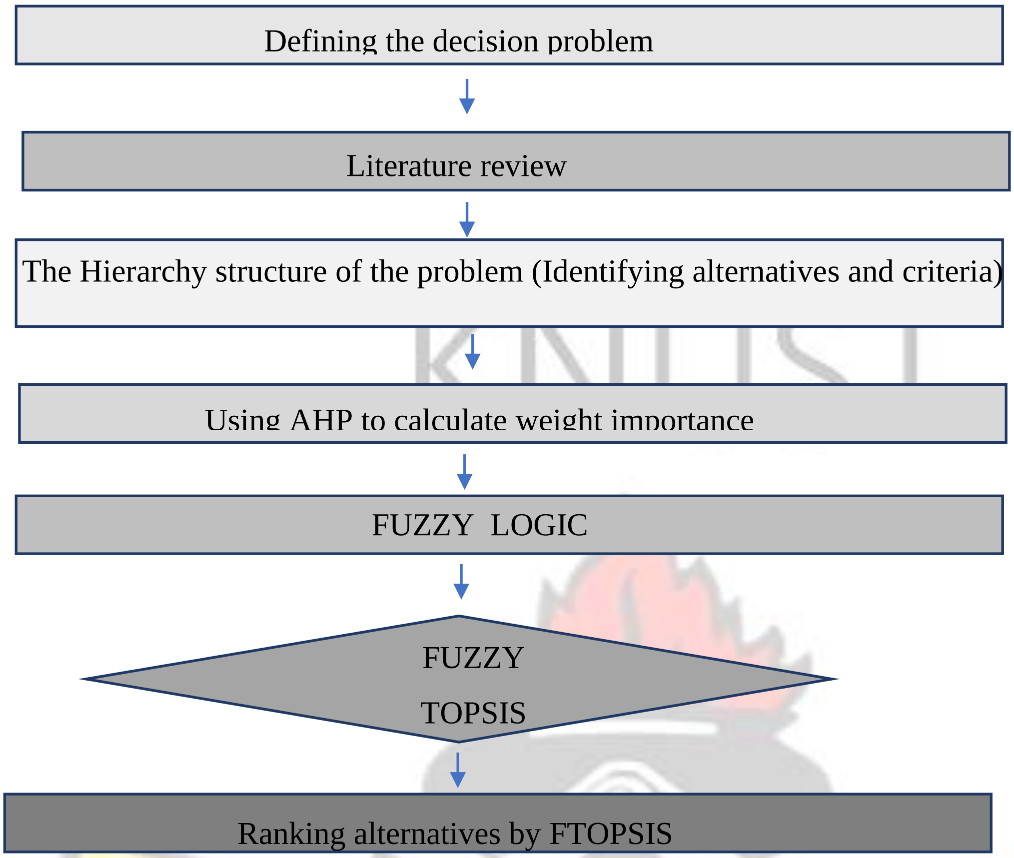

Figure 3.9: Hybrid framework of the study

3.13.3 Application of the hybrid AHP and fuzzy TOPSIS to the study

The AHP method is applied first followed by the FTOPSIS in the steps below.

Step 1: Problem identification. Selection a digester for anaerobic digester

Step 2: Establishing the decision-making criteria. These criteria (objectives) with their objectives were used for all the three scenarios in the selection of the alternatives as justified in the scenario planning procedure above.

Table 3.1: The criteria selected for the case of the scenarios in this study

Symbol	Criteria	Objective		
		Scenario 1	**Scenario 2**	**Scenario 3**
C_1	COD/Vs Reduction Efficiency	Maximize	Maximize	Maximize
C_2	Retention of Residual Nutrients	Minimize	Minimize	Maximize
C_3	Total Solids content in the Digester	Minimize	Minimize	Minimize
C_4	Organic Loading Capacity	Maximize	Maximize	Maximize
C_5	Axial Mixing	Minimize	Minimize	Minimize
C_6	Biogas Yield	Minimize	Maximize	Minimize
C_7	Stage of Treatment (Primary and Secondary)	Maximize	Maximize	Maximize
C_8	Thermal Stability of the system	Maximize	Maximize	Maximize

Step 3: Establish alternatives for the decision-making process. Identify the set of alternatives that can be used and present the data in the alternative's matrix A = [Ai]. Where i = 1...n, represents the number of alternatives.

Table 3.2: Screened alternative digesters

Symbol	Alternative
A_1	Anaerobic Fluidized Bed Reactor (AFBR)
A_2	Anaerobic Plug Flow Reactor (APFR)
A_3	Expanded Granular Sludge Bed (EGSB)
A_4	Internal Circulating Reactor (ICR)
A_5	Up-flow Anaerobic Sludge Bed (UASB)
A_6	Up-flow Baffled Reactor (ABR)
A_7	Anaerobic Filter (AF)

Step 4: Compare the criteria in pairs and determine the relative weight of Criteria

The relative weight of the criteria c = [*cij*] is determined and their importance in the decision-making process.

Table 3.3: Fundamental scale of Thomas L. Saaty (Saaty, 1980).

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over the other	Experience and judgment slightly favor one activity over the other
5	Essential or Strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	Activity is strongly favored and its dominance demonstrated in practice
9	Absolute important	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6 &8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above nonzero	If activity 1 has one of the above nonzero numbers assigned to it when compared with activity j, then has the reciprocal value when compared with i.	

Then perform a pairwise comparison to assess the pairs subjectively.

Develop a square matrix from the data with "*m*" elements, where "*m*" is the number of decisional criteria. Perform the calculations for the ratios 1/2…1/9 and obtain a different matrix of pairwise comparisons between various criteria. Also, this matrix shall contain the total on every column, which is calculated based on the following formula:

$$Sj = \sum_{j=1}^{m} cji \tag{16}$$

Step 5: Normalize the comparisons between criteria. The normalized figures ''*nij*'' can be achieved by calculation based on the following formula:

$$nij = \frac{cij}{Sj} \tag{17}$$

The pairwise comparison between criteria is transformed into weights, these weights are then computed as an average of the normalized figures on each row, using the Formula (7), as follows:

$$kj = \frac{\sum_{j=1}^{m} nji}{m} \tag{18}$$

where: *kj* = the importance coefficients (weights) of the decision criteria. The following condition must be achieved under conditions were normalized values are used,

$$\sum_{j=1}^{m} kj = 1 \tag{19}$$

Step 6: The consistency factor of the decision criteria matrix is determined by performing the following steps

a) Determine the vector of priorities - λmax. The vector of priorities is calculated using Formula (9), as follows:

$$\lambda max = \sum_{j=1}^{m} \frac{(c.k)j}{m.kj} \tag{20}$$

where: *(c · k)j* represent the elements of the matrix-vector determined as a result of multiplying the "*c*" matrix with "*k*" vector.

b) Determine the uniformity coefficient. The uniformity coefficient "*CI*" is calculated based on the equations that follows:

Step 7: The vagueness and uncertainties of judgment are addressed comprehensively by introducing fuzziness to the process. Table 3.7 and Table 3.8 were reconstructed using the required TFN linguistic variables. According to Chen's approach, the procedure of fuzzy TOPSIS can be expressed in the steps below**:**

Step 7. 1 Assign linguistic variables to alternatives. This step is associated with assigning the linguistic variables for the alternatives due to the criteria which are given in Tables 3.4 and 3.5, construct a fuzzy matrix of alternative**s.**

Linguistic variables

The TOPSIS method can be extended in the fuzzy environment by representing the weights of each of the criteria obtained from the AHP method and the alternatives under consideration as linguistic variables.

Table 3.4: Linguistic variables for the ratings.

Linguistic Variable	**Range**
Very low (VL)	(0.1, 0, 0)
Low (L)	(0.3, 0.1, 0.1)
Medium low (ML)	(0.5, 0.3, 0.3)
Medium (M)	(0.7 ,0.5, 0.5)
Medium high (MH)	(0.9, 0.7, 0.7)
High (H)	(1, 0.9, 0.9)
Very high (VH)	(1, 1, 1)

Table 3.5: Linguistic variables for the ratings.

Linguistic Variable	Range
Very poor (VP)	(1, 0, 0)
Poor (P)	(3, 1, 1)
Medium poor (MP)	(5, 3, 3)
Fair (F)	(7, 5, 5)
Medium good (MG)	(9, 7, 7)
Good (G)	(10, 9, 9)
Very good (VG)	(10, 10, 10)

Step 7.2: Convert fuzzy linguistic terms to crisp one

In this method, the fuzzy linguistic terms utilized by decision-makers (experts) should translate to a crisp one according to the range of value illustrated in Table 2. Then, the comparison matrix will be as follows

$$\tilde{A} = \begin{bmatrix} x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \\ x_{m1} & x_{m2} & x_{m3} \end{bmatrix} \tag{21}$$

Step 7.3. Construct the fuzzy normalized matrix.

In order to get a comparable scale, a linear scale transformation is used for positive and negative indicators, respectively:

$$\tilde{R} = (\tilde{r}_{ij})_{mxn}$$

$$\tilde{r}_{ij} = \left[\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right], \quad c_j^* = max c_j^*$$

$$where\ j = 1,2,3 \ldots \ldots n \quad and \quad i = 1,2,3 \ldots \ldots m$$

$$\tilde{r}_{ij} = \left[\frac{a_j}{c_{ij}^*}, \frac{b_j}{c_{ij}^*}, \frac{c_j}{c_{ij}^*}\right], \quad a_j^* = min\, ai_j^*$$

$$where\ j = 1,2,3 \ldots \ldots n \quad and \quad i = 1,2,3 \ldots \ldots m \tag{22}$$

Step 7.4: Construct a weighted normalized decision matrix.

Supposed that $\breve{W}_j = \breve{w}_1, w_2, w_{3,\dots\dots,} w_n$ is the weight of importance of decision-maker and$\sum_j^n = 1 \; then \, \breve{W}_j = 1, V = \left[(v_{ij})_{mxn} \right]$ is the weighted normalized decision matrix where $i = 1,2, \dots\dots, m$ and $j = 1,2, \dots\dots, n$ it can be computed by utilizing the given equ (14)

$$V_{ij} = \tilde{r}_{ij} x \, \tilde{w}_j \tag{23}$$

Step 7.5: Calculate the fuzzy positive (FPIS) and fuzzy negative ideal solution (FNIS) The FPIS and FNIS for alternatives can be determined as follows:

$$A^* = v_1^*, v_2^*, \dots . v_n^* \;\; j = 1,2.3, \dots \dots . n \tag{24}$$

$$A^- = v_1^-, v_2^-, \dots . v_n^- \;\; j = 1,2.3, \dots \dots . m \tag{25}$$

Step 7.6. Calculating the distance of each choice from FPIS (A^*) and FNIS(A^-) thus the separation measure. Calculating the distance of each weighted alternatives from FPIS and FNIS is possible by the following equations:

$$S_i^* = \sum_j^n = 1 \, , d\left(\tilde{v}_{ij}, v_j^*\right) \, i = 1,2, \dots . , m \tag{26}$$

$$S_i^- = \sum_j^n = 1 \, , d\left(\tilde{v}_{ij}, v_j^-\right) \, i = 1,2, \dots . , m \tag{27}$$

$$d\left(\tilde{a}_{ij}, \tilde{b}_{ij}\right) = \sqrt{\frac{1}{3}(a1_{ij} - b1_{ij})^2 + (a2_{ij} - b2_{ij})^2 + (a3_{ij} - b3_{ij})^2} \tag{28}$$

$$\tilde{a} = (a1_{ij}, a2_{ij}, a3_{ij}) \; and \; \tilde{b} = (b1_{ij}, b2_{ij}, b3_{ij})$$

Step 7.6. Calculating each alternative Closeness Coefficient (CC^*) which represents the similarity to an ideal solution and it can be determined as follows:

$$= CC^* \frac{S^-}{S^* + S^-} \tag{29}$$

Step 7.7. Ranking the alternatives. Ranking the different alternatives by utilizing CC^*on a decreasing order.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 General Overview

This section of the study focuses on the results from the application of scenario planning, the AR technique, AHP, and Fuzzy TOPSIS for selection and synthesis of the anaerobic digester.

4.2 Application of feasibility assessment tool to the study

4.2.1 Critical dimensions

The scenario gave certain idea about prospects of developing of the economic and social system they were developed for. Most often scenarios are a qualitative projection where some extremely important qualitative estimates are allowed and required. Thus, the scenario planning differs from forecasting that emphasizes the variety of stipulated qualitative indicators. The method of scenarios has shown to be useful when defining goals of projects, its development strategy, as well as during the long-term forecasting when current achievements do not matter, and it is more important to apply new opportunities. The sanitation scenario ensured the reduction of environmental pollution. It analyzed the potential of the numerous existing digesters to treat waste without leaving any trace of dangerous chemical in the effluents which would in turn harm the environment. It further focused on the main factors that have an impact on the promoting environmental sanitation.

Energy scenarios were used both by industries and individuals that form the strategy of the complex development in the area of renewable energy. In this case, the potential of the digesters to prioduce maximum methanae was magnified over the other factors which makes the digester an efficient one. The nutrients recovery scenario was related to the ability of a treatment system to produce richsterilized effluents for farmlands. Summary descriptions of the unfolding processes propelling the scenarios are also presented. The plot descriptions as shown in Figure 4.1 to Figure 4.3 below were made with reference to the twelve driving forces explained in chapter 3 above. The values that determine the performance of the Critical dimensions ranged from zero to three. (3, strongly important; 2, somewhat important; 1, important; 0, not relevant). They were the basic indicators used to access the suitability and sustainability of alternative parameter that is likely to affect a particular scenario in a critical way. Depending on the indicator, higher values may be better or worse with respect to anaerobic digester selection goals as justified in the tables 4.1 to 4.3 below. The justification influences reason why a specific operating condition is preferred over the other in a scenario.

Table 4.1 Justification of scores in scenario 1 (Sustainable Waste Management).

Critical Dimension	**Score (3, strongly important; 2, somewhat important; 1, not relevant)**
COD/Vs Reduction Efficiency	**3;** Research has consistently shown that levels of Biological Oxygen Demand (BOD) are determined based on the rate of organic pollution. The preferred digester should effectively remove or leave a smaller number of reduced compounds in the effluent for a safer and hygienic environment.
Retention of Residual Nutrients	**3;** Sustainable waste management aims at providing a healthy environment, hence the presence of pollutants in the influent must undergo thorough biodegradability phase to recover useful agricultural nutrients before they are discharged in the environment.
Total Solids content in the Digester	**3;** The consistency of waste available for treatment would determine the type of digester to use in relation to their fermentation process. Continuously Stirred Tank Reactor (CSTR). CSTR systems are applied in practice for treating animal waste, industrial waste, household waste, agricultural wastes, faeces or blend of these substrates whereas plug flow digesters are use slurries as feedstock, example undiluted waste which has total suspended solids concentration of 10-12% TS Dry matter / total solids (DM / TS) below 15% in the process Requires low DM substrate or good degrading feedstock
Organic Loading Capacity	**3;** A digester with high loading capacity is required because of the millions of tonnes of waste that may be treated**.**

Axial Mixing	**3;** Anaerobic Digesters do have different operation mood depending on the type of digester to be selected for the process. According to Abunde et al, there exist mixing reactors (CSTR and Fed-Batch) and reaction reactors thus no axial mixing occurs within the system (APFR, UASB, EGSB, ABR, and ASBR).
Biogas Yield	**1;** Biogas yield potential of waste and digester is not of much interest as far us the aim of the treatment process is sanitation.this dimension was however included because there is always an amount of biogas produced whenever anaerobic digestion takes place.
Stage of Treatment	**3;** Secondary treatment is used for nutrient removal (nitrogen), hygienisation, and education of chemical oxygen demand (COD) and biological oxygen demand (BOD) for a healthy ecosystem
Thermal Stability of the system	**3;** For the purpose of this studies, Ambient/seasonal temperature AD would be used even though it exhibits lower methane production and lower stability. This is very practical and it translates the prevailing environmental conditions we have in every country.

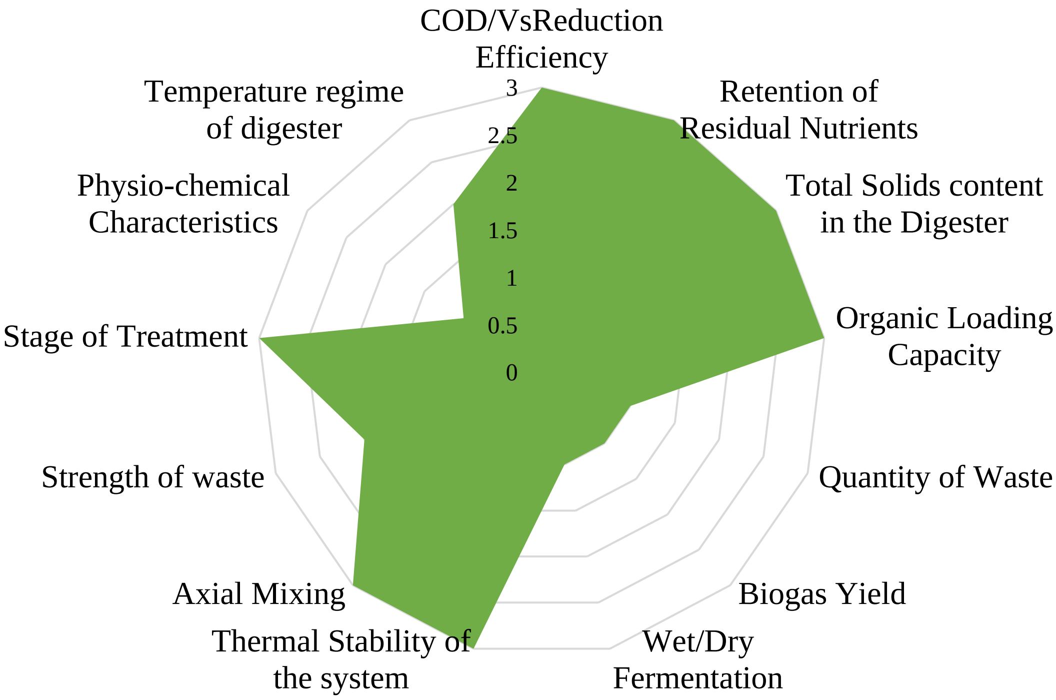

Figure 4.1: Justification for critical dimension (scenario 1)

Table 4.2 Justification of scores in scenario 2 (Renewable Energy Generation)

Critical Dimension	Score **(**3, strongly important; 2, somewhat important; 1, not relevant)
COD/Vs Reduction Efficiency	**3**; The rate of methane production depends on the rate of removed COD The Chemical Oxygen Demand (COD) is used to quantify the amount of organic matter in waste streams and predict the potential for biogas productions.
Retention of Residual Nutrients	**0;** Not relevant to this scenario
Total Solids content in the Digester	**3;** Wet fermentation systems are preferred because of the consistencies of waste predominant for the process including various types of waste.
Organic Loading Capacity	**3;** The organic loading capacity has a link with the quantity of waste to be degraded
Axial Mixing	**3;** Cumulative increase in biogas production increases with agitation and how frequent the system is agitated. This improves the activity of bacteria through the release of biogas and provision of fresh nutrients and also mixes fresh and fermenting substrate
Biogas Yield	**3;** Digester with high biogas yield efficiencies are recommended for this scenario because Methane yield is closely related to the reactor type.
Stage of Treatment	**3;** Primary treatment is usually done for removal of settleable and digestible solids and organic matter which in turn produces biogas. These could be done in biogas settler, biogas septic tank and other types of reactors.
Thermal Stability of the system	**2;** Digesters should be stable irrespective of the prevailing weather conditions, even though ambient conditions affect the production of biogas due to the temperature variation of its surrounding environment**.**

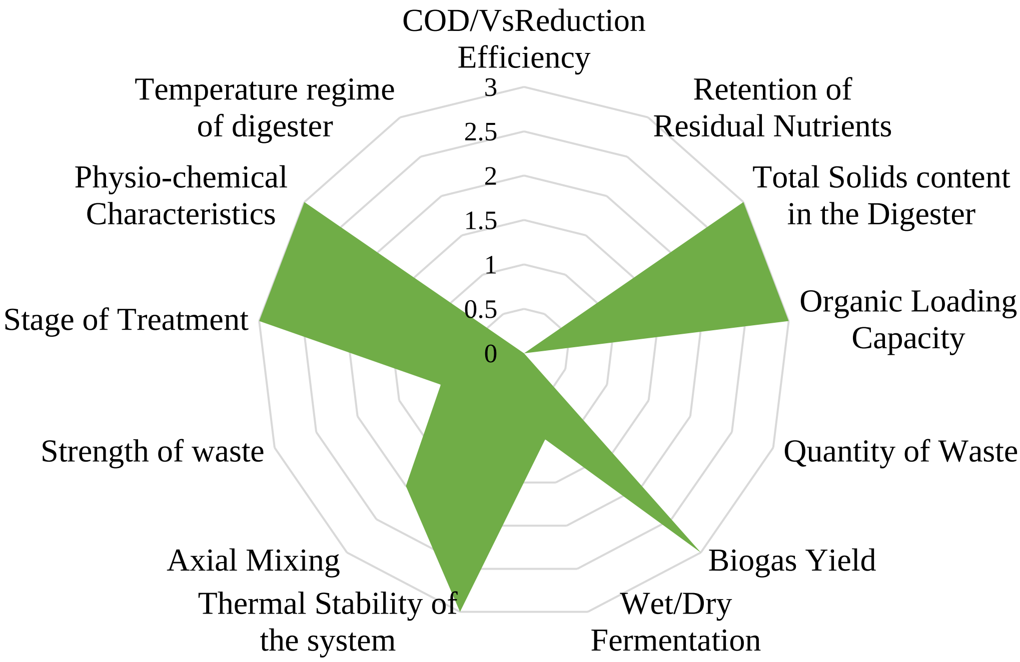

Figure 4.2 Justification for critical dimensions for scenario 2

Table 4.3 Justification for critical dimension scenario 3 (Nutrient recovery)

Critical Dimension	Score (3, strongly important; 2, somewhat important; 1, not relevant)
COD/Vs Reduction Efficiency	2; The function of anaerobic bioreactor designed for nutrient recovery is not limited by its COD/VS reduction efficiency.
Residual Nutrients	**3;** Appropriate AD digester for nutrients recovery facilitates the mobilization of nutrients from the organic matter to preserve and recover nutrients for reuse.
Wet/Dry Fermentation	**3;** Wet fermentation systems are preferred because of the consistencies of waste predominant for the process. (all possible waste types)
Organic Loading Capacity	**2;** The anaerobic digester selected should not be limited by its organic loading capacity**.**
Agitation/Reaction	**3;** To avoid and destroy swimming and sinking layers, inoculate the biomass to arrive at even distribution of temperature thus providing uniform conditions inside the digester, then agitation must be done as often as possible.
Biogas Yield	**1;** Biogas is produced as an added advantage when treating the waste for nutrient recovery**.**
Stage of Treatment	**3;** Secondary treatment is preferred for this scenario because of its efficacy to remove pollutant and recover nutrients.
Thermal Stability of the system	**2;** Digesters should be stable irrespective of the prevailing weather conditions, even though ambient conditions affect the production of biogas due to the temperature variation of its surrounding environment**.**

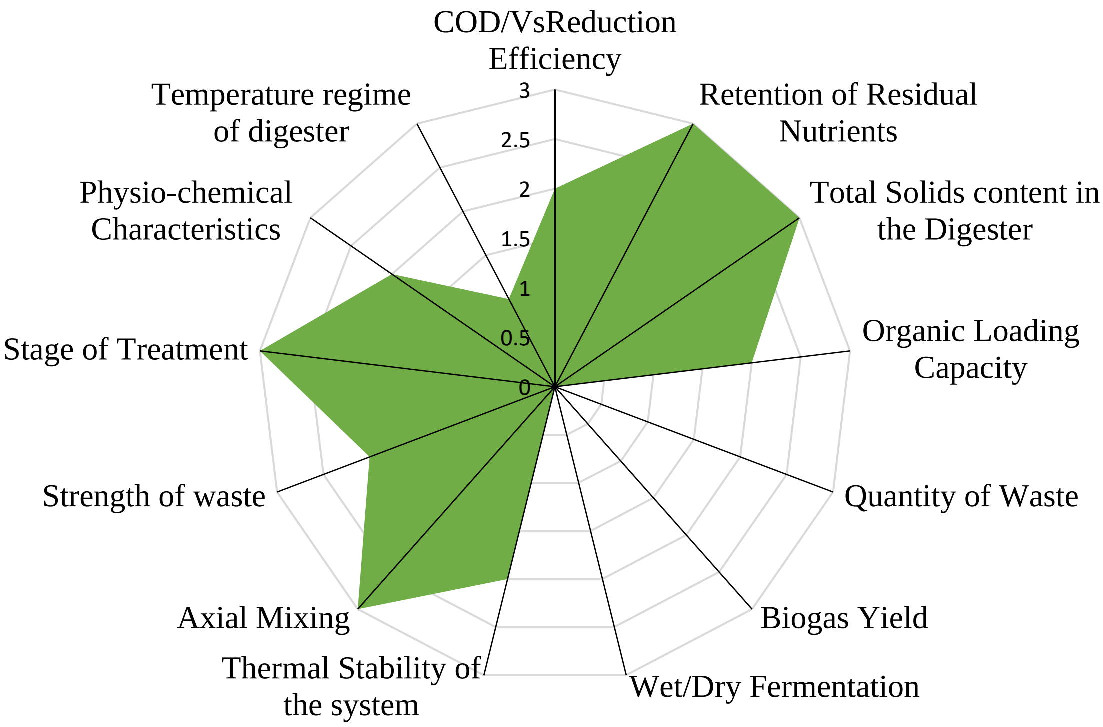

Figure 4.3: Justification for critical dimension in nutrients recovery for farmlands

4.3 Physical-chemical characterization of substrate

The table below shows the results for waste characterization which determines the suitability and profitability of the various feedstock for biogas production. The measurements were made using the methodology presented in chapter 3. The values obtained for the pineapple waste as shown in Table 4.1 are slightly different from the literature, as mentioned by Laura et al as well as Pilarski *et al.*, (2009) and Pamjai *et al.*, (2013) on waste Characterization. The difference in value may be due to the variety of the pineapple used and the difference in origin of the source, in the case of food waste, the composition was also different. The abattoir waste and pig manure, saw variations which would obviously be due to the composition of the feed intake by the animal.

Table 4. 1 Characterisation of substrates

Parameters	Pineapple Waste	Abattoir Waste	Pig Manure	Food Waste
Total Alkalinity (ppm)	1500	1650	3500	2010
TDS (ppm)	387.1	220	678	294
BOD (ppm)	934.1	520	599.4	224
COD (ppm)	1368	740	936.1	336
Protein (mm/kg)	5.768	27.6	7.3115	9.3255
Crude Fibre (mm/kg)	9.107	13.96	31.485	6.3795
Carbohydrate (mm/kg)	78.945	44.48	34.32	79.355
Moisture (%)	84.75	82.49	61.91	83.43
Total Ash (mm/kg)	12.55	3.926	25.03	3.035
Fat (mm/kg)	1.2	2.25	1.85	1.9
Volatile Solids (%)	96.075	87.41	74.97	96.95
Total Solids (ppm)	15.254	17.515	38.0986	16.568
Ca (mm/kg)	0.11	0.1	0.08	0.08
Mg (mm/kg)	0.32	0.74	0.34	0.37
S(mm/kg)	0.55	0.5	0.4	0.41
P (mm/kg)	0.53	0.4	0.76	0.65
Fe (mm/kg)	84.5	114.6	128.1	85.3
Cu (mm/kg)	10.2	9.1	8.9	8.8
Zn (mm/kg)	50.37	39.19	48.2	36.47
Ni (mm/kg)	0.01	0.04	0.02	0.01
Mn (mm/kg)	14.1	22.9	14.3	12.8
K (ppm)	1.48	1.25	1.65	1.52
N (ppm)	0.22	2.02	0.2	1.71

4.4 Cumulative biogas production

The graphical representation of the cumulative data is shown in Figures 4.2 to Figure 4.5. The minimum value obtained on the first day was $2 \times 10^{-6} m^3$ for pig manure feedstock and the maximum was $0.014\ m^3$ which was obtained on seventeenth day. Abattoir waste feedstock started producing gas on the second day until day nineteen from $5 \times 10^{-6} m^3$to $0.012\ m^3$. The pineapple peels feedstock, however, started producing biogas from day one and it increased on day twenty one from $4 \times 10^{-6} m^3$ to $0.009\ m^3$. Food waste produced a lot of gas from the first day until day nine from, $1 \times 10^{-6} m^3\ to\ 0.006\ m^3$. The overall production variation is associated with the composition differences of the substrates per Table 4.2 because the biogas production rates, are variables that depend directly on the quantity and characteristics of the residues that are fed to biodigester (Kalia, 2008). According to Bernal *et al.* (1992), biogas yield is directly proportional to the process efficiency. However, it is also important to note that a low biogas yield does not necessarily indicate a deficient performance but it could be due to a low biodegradability of the substrate used.

Table 4.5 Biogas production rate of substrates

Retention Period (Day)	Pig manure (Litres)	Abattoir Waste (Litres)	Pineapple Waste (Litres)	Food waste (Litres)
1	0	0	0.45	1.2
2	0.002	0	1.35	2.9
3	0.08	0.005	3.2	3.4
4	0.14	0.03	4.9	3.5
5	0.16	0.12	4.9	4
6	0.64	0.48	7.2	5.4
7	1	0.76	7.2	5.7
9	3	1.53	7.9	5.9
10	5.2	2.78	7.9	5.9
11	7.5	4.3	7.9	5.9
12	10.2	5.4	8.4	5.9
13	11.42	7.3	8.5	5.9
14	12.9	8.2	8.5	5.9
15	13.06	9	8.5	5.9
16	13.15	10.53	8.7	5.9
17	13.87	11.02	8.7	5.9
18	13.87	11.54	8.7	5.9
19	13.87	11.63	8.7	5.9
20	13.87	11.91	8.7	5.9
21	13.87	11.91	8.9	5.9
22	13.87	11.91	8.9	5.9
23	13.87	11.91	8.9	5.9
24	13.87	11.91	8.9	5.9
25	13.87	11.91	8.9	5.9
26	13.87	11.91	8.9	5.9
27	13.87	11.91	8.9	5.9
28	13.87	11.91	8.9	5.9
29	13.87	11.91	8.9	5.9
30	13.87	13.38	8.9	5.9

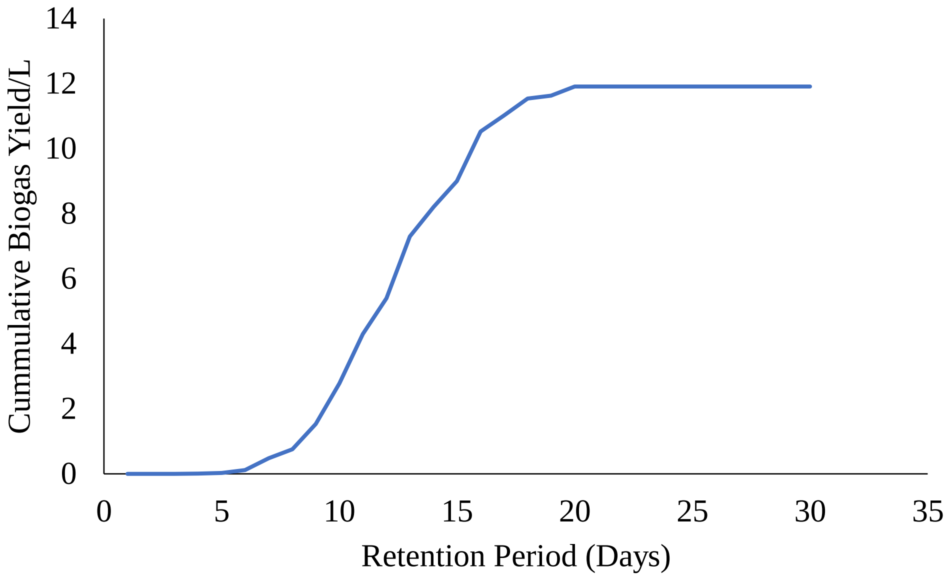

Figure 4.4: Cumulative biogas production curve for abattoir waste

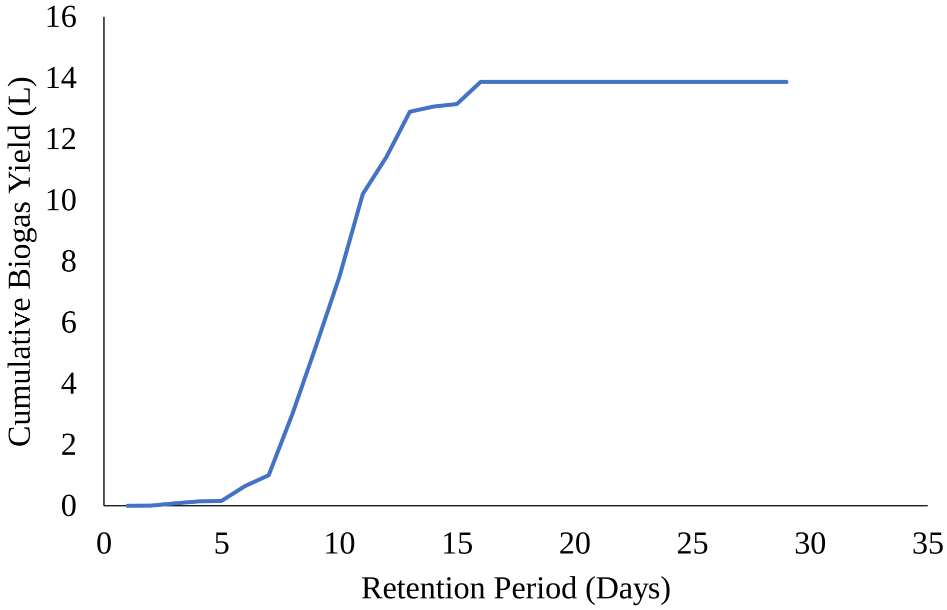

Figure 4.5: Cumulative biogas production curve for pig waste

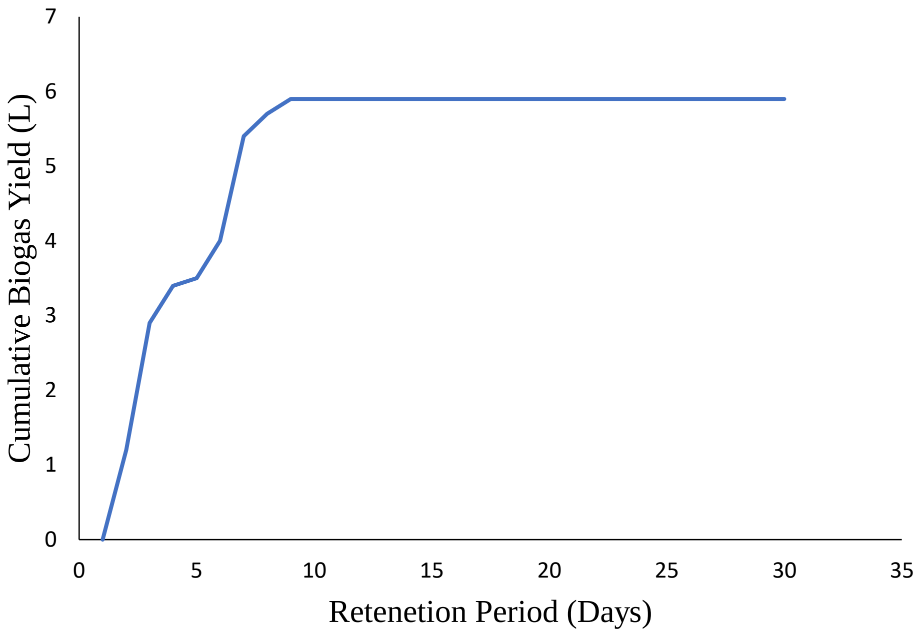

Figure 4.6: Cumulative biogas production curve for food waste

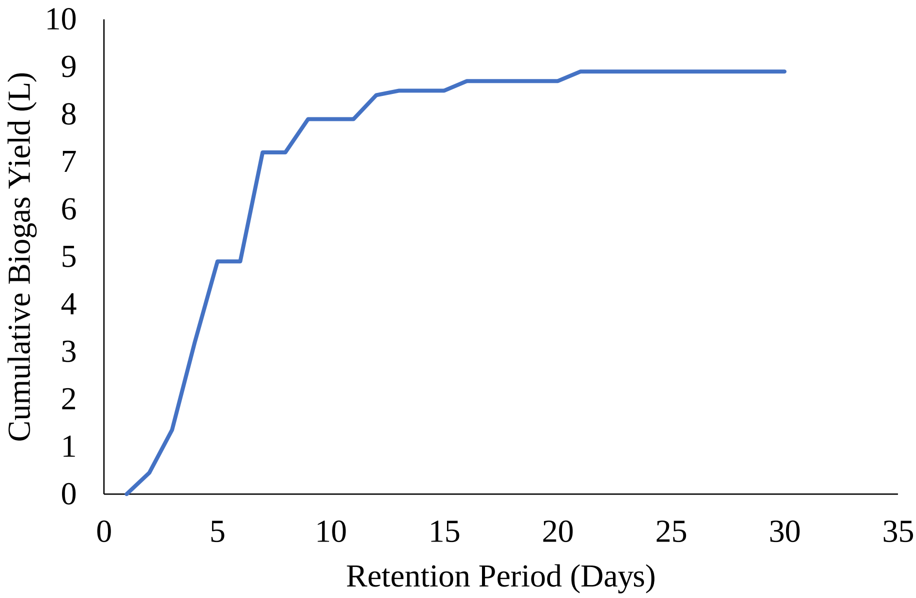

Figure 4.7 Cumulative biogas production curve for pineapple waste

4.5 Generalised digester structure

The design of the optimal digester structure was to minimize digestion time using the three main aspects: (1) Construction of attainable regions using geometric techniques, (2) scheduling of batch operation from the attainable regions, and (3) Interpretation of continuous mode operation structures from the batch operation and Continuous operations.

The point A on the curve represents a digester condition where a fresh mass of substrate has just been added and no biogas has been produced. The straight-line AC, therefore, represents a batch digester, which is a run-up to a certain residence time then the content is mixed with fresh substrate. Since the base anaerobic trajectory on top of the residence time axis than the stirring line AC, bypassing fresh organic substrate reduces the overall residence for the same cumulative biogas yield (this is only for yields between points A and C). For example on the initial anaerobic digestion trajectory, observe that a residence time of 10days is required to obtain a cumulative biogas yield of 0.5mL/g, meanwhile the same yield can be achieved at 5days using the mixing line. It can be reached by operating the batch digester up to point C and then mixing fresh substrate with this flow to get the total yield. It should, however, be noted that this optimization is only possible because of the concave nature in the original anaerobic digestion trajectory, and hence regions of low digestion rate in the digester are to be bypassed by the use of mixing. This phenomenon can be attributed to the fact that adding fresh substrate increases nutrient bioavailability for the anaerobic microorganisms thereby increasing growth and hence the production of the desired biogas

From step 2 how graphical techniques were applied to expand the total set biogas yields that are achievable in the anaerobic digester by making use of concavities in cumulative biogas yield curves. Furthermore, from the principles of differential algebra, process trajectories from batch reactors are directional. Geometrically, the reaction rate vectors of batch processes have a unique nature, which ensures that different batch trajectories progress in a manner that they do not cross one another. For a given feed point there exists a unique trajectory for a process operated in batch mode. To reduce the overall system residence time, the ABCD curve was moved down using the base trajectory means, until the curve justs in touch with the stirring line given by AC, which is displayed in Figure 4.8 by point E. Point E shows the lowest residence time of the current candidate region which runs an additional PFR to expand the region.

The same procedure was repeated for the other three organic substrates and the attainable regions are presented in Figure 4.8. The base anaerobic digestion trajectory of pig manure is similar to that of abattoir waste, and hence the construction of the attainable regions will be similar. Figure 4.9 presents the attainable region for pineapple waste,

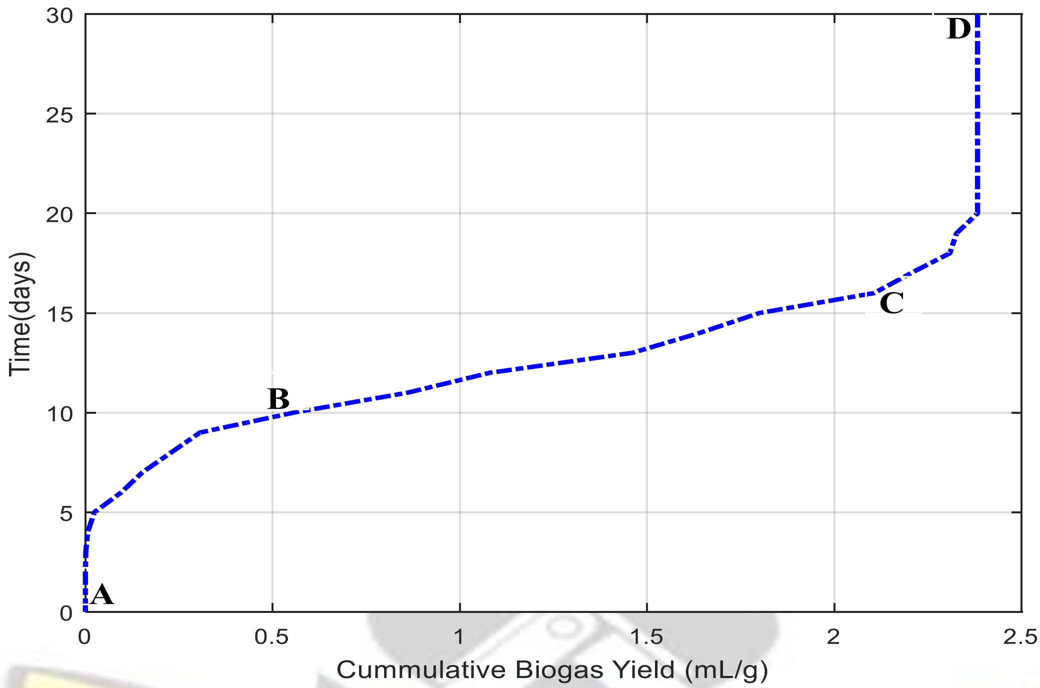

Figure 4.8: Base anaerobic digestion trajectory in ar convention

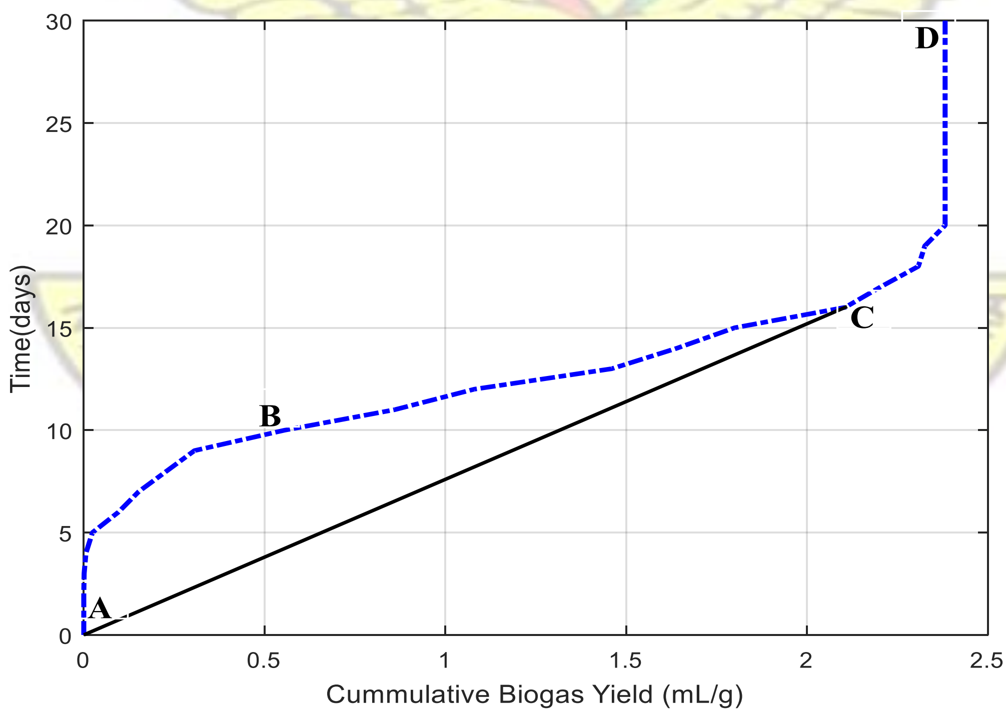

Figure 4.9: Base anaerobic digestion trajectory showing mixing line

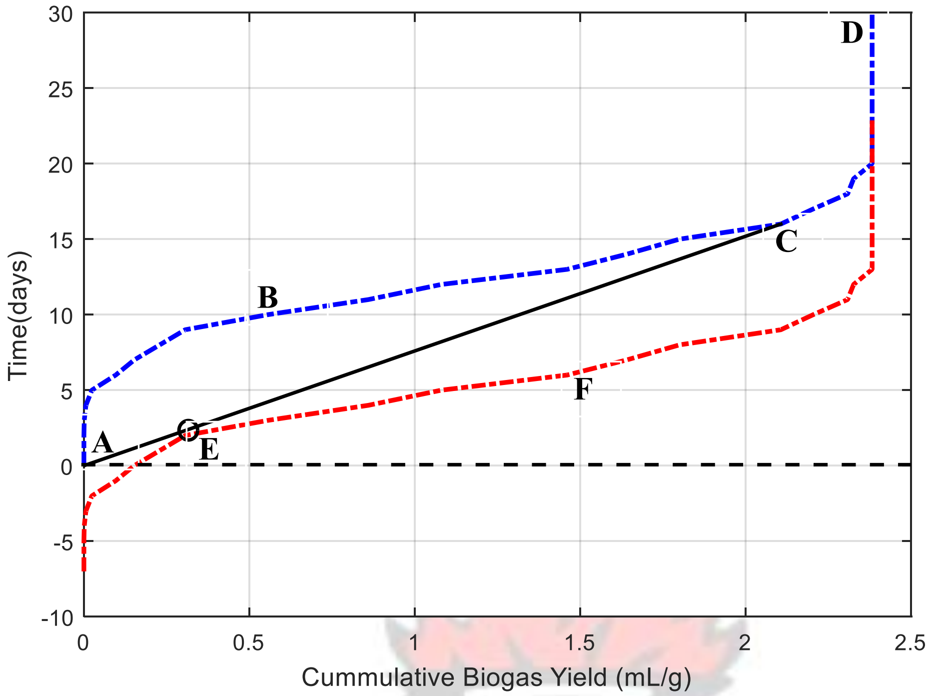

Figure 4.10: Further optimization using progressive batch trajectory and the mixing line

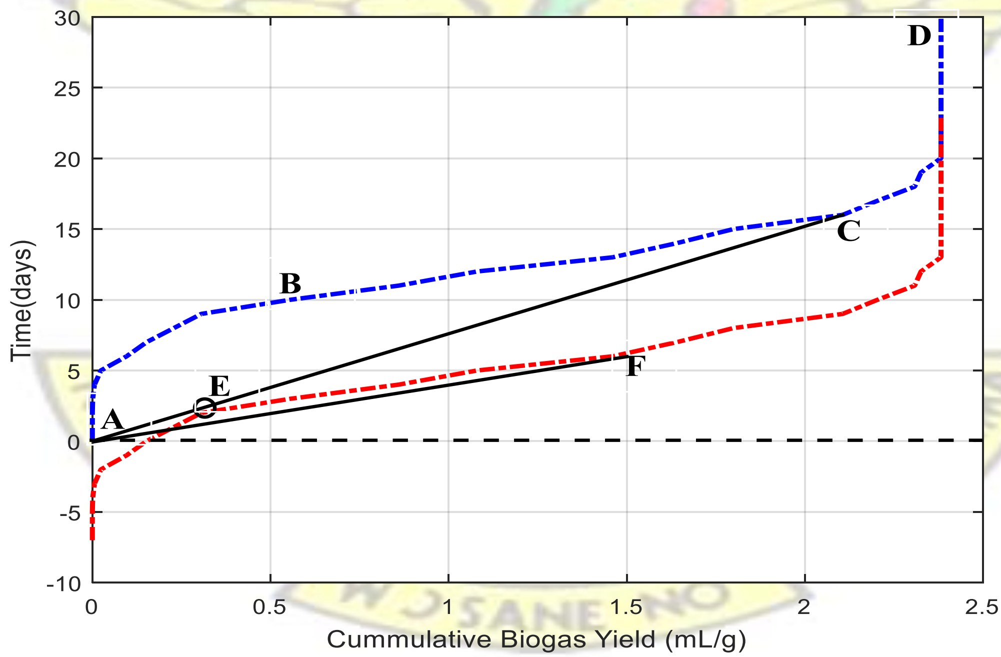

Figure 4.11: Attainable region for the anaerobic treatment process.

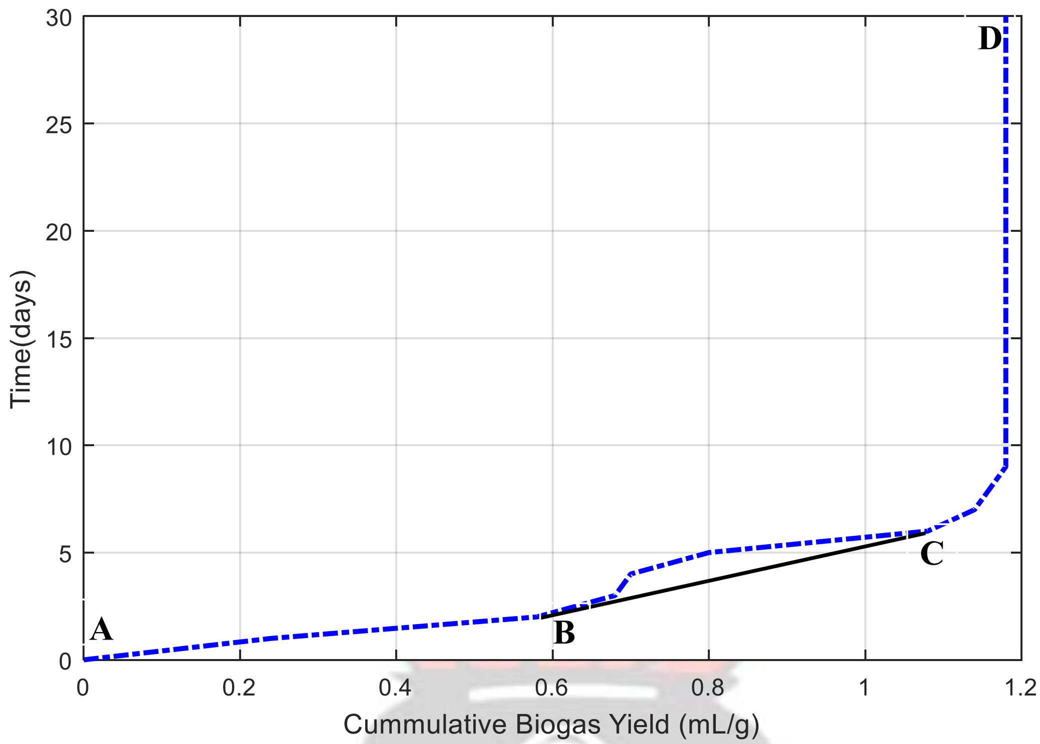

Figure 4.12: Attainable region for anaerobic treatment of pineapple waste

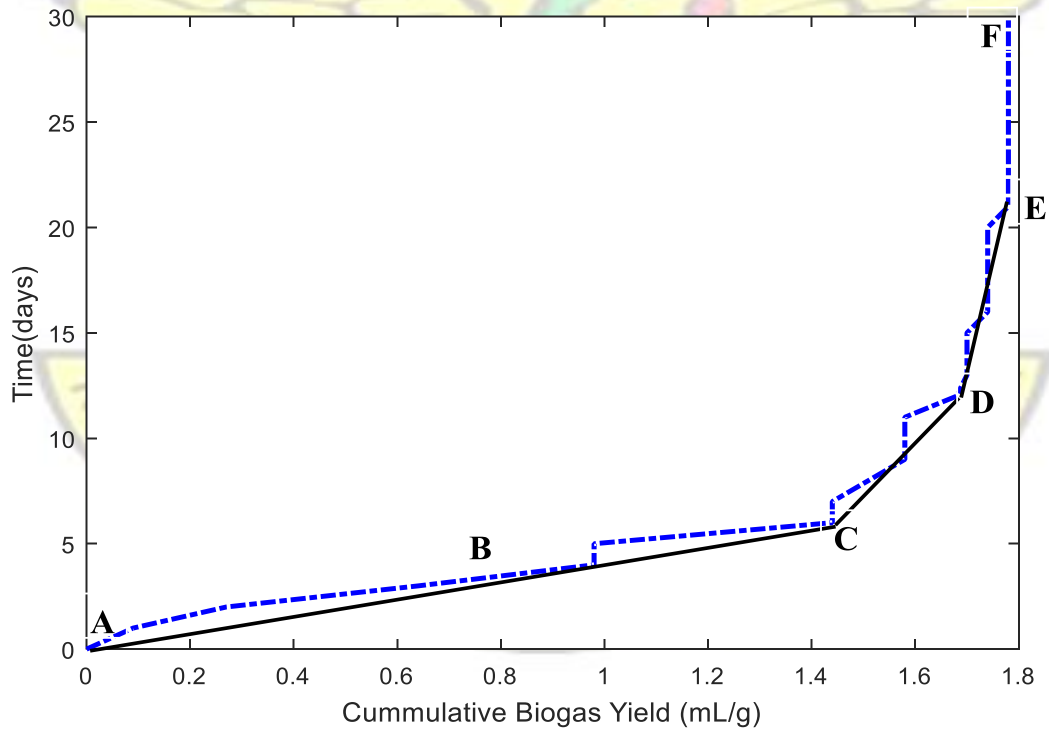

Figure 4.13: Attainable region for anaerobic treatment of food waste

4.5.2 Batch operation scheduling

The respective network configurations needed for optimal performance in the batch operation schedules are shown in the schematic diagrams below. Three CSTRs connected in series would be needed for the digestion of abattoir waste and pig waste. A combination of parallel and series network system was designed for the food waste and pineapple waste to optimize its performance.

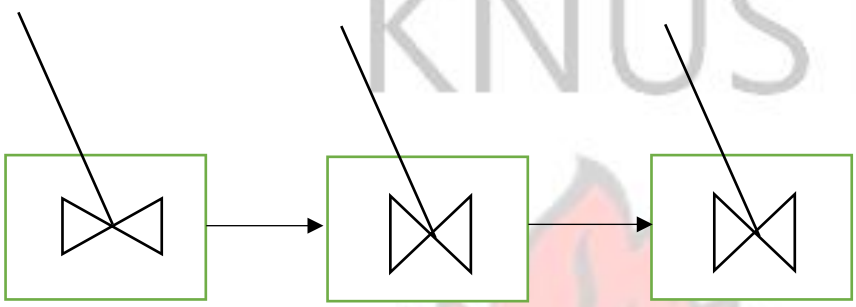

Figure 4.14: Batch digestion abattoir and pig waste

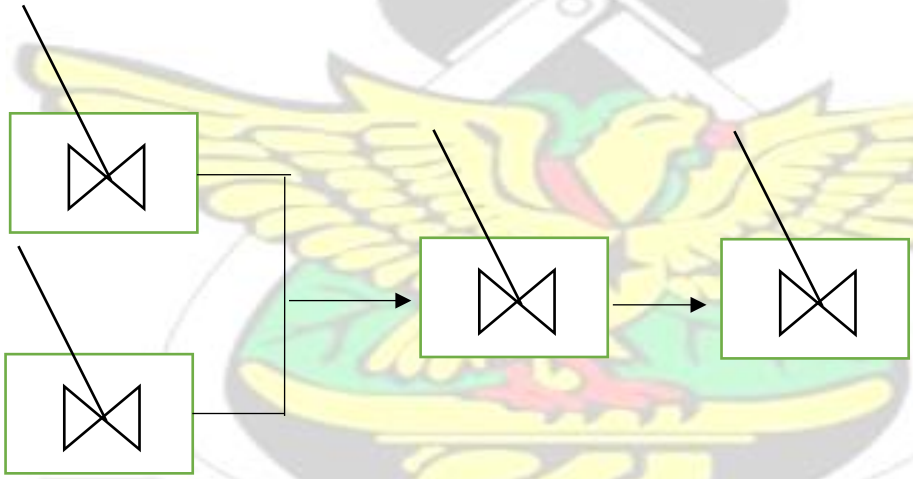

Figure 4.17: Batch digestion food and pineapple waste

4.5.3 Continuous mode operation

The continuous mode operation option had different designs as shown in Fig. 5.15 to 4.17. Abattoir and pig waste had a series combination of one CSTR and one PFR as recycling system in its design. The design for food waste and pineapple waste was also a combination of two parallel connected CSTRs in series with one PFR working together as a bypass system.

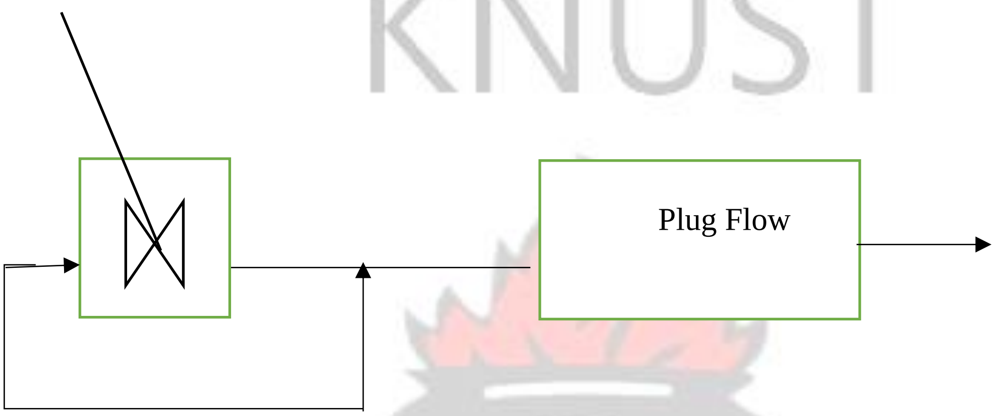

Figure 4.17: Continuous operation for abattoir and pig waste

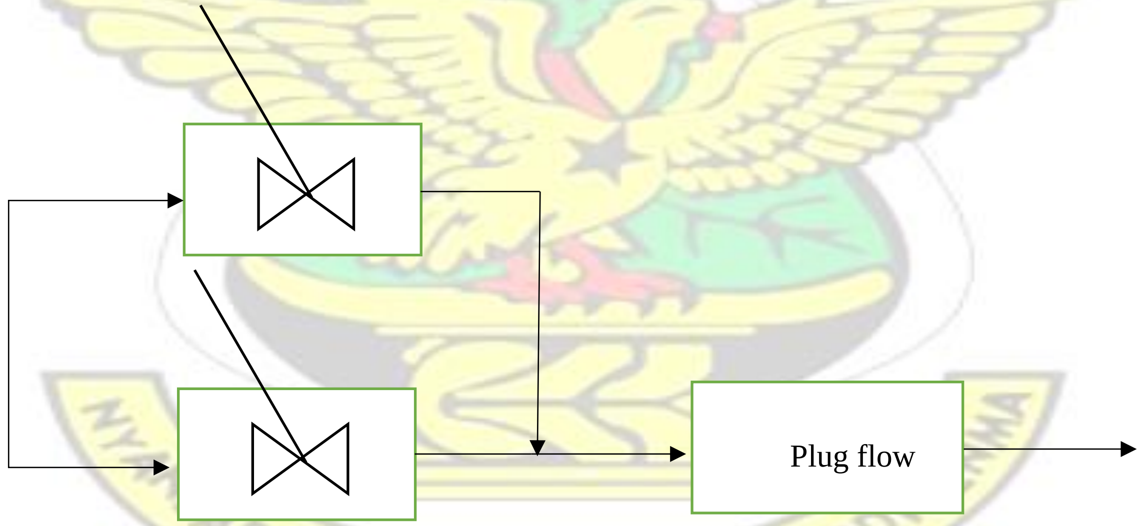

Figure 4.19: Continuous operation food and pineapple waste

4.6 Digester sub unit

MCDA tool was developed using Microsoft Xcel. Tables 4.3 to Table 4.5 presents the pairwise comparison between criteria for scenarios using the judgemental scale of Saaty, 1980 as presented in Table 3.1 in Chapter 3. Referring to the general objective of the study, the weight of each criterion was based on technical knowledge and general operating conditions of anaerobic waste treatment for sanitation purposes. Some of these operational conditions selected as criteria have been applied by researchers. For instance, in the selection of an anaerobic digester for sanitation purposes, the efficiency of the digester (COD/VS reduction efficiency of digester, the stage of treatment at which a particular digester would be more efficient and the organic loading capacity of the digester) is more important to be considered than the biogas yield capacity of digester in this scenario. This makes a value of 9 to be given in the comparison between C1 and C6. In filling the matrix, if C1 is 9 times more preferred to C6, then C6 is 1/9 times more preferred to C1. In that case, as C1 gets a judgemental value of 9, C6 gets the inverse which is 1/9. It is, the judgemental scale is 1 when a criterion is compared by itself and, this is the reason why the value, 1 is recorded on the matrix' diagonal (Constantin *et al.*, 2010). Moving on with the studies, the decision criteria matrix was normalized (Table 4.2) and transformed in weights to know the extent to which each criterion has on the selection of anaerobic digester. This was achieved in accordance with ***step 5*** as presented in Chapter 3.

Table 4.6: Results for pairwise comparison between criteria for scenario 1 (decision criteria matrix)

Criteria for Selection	C1	C2	C3	C4	C5	C6	C7	C8
C1	1	1	5	1	3	9	1	3
C2	1	1	7	3	5	7	1	3
C3	0.2	0.14	1	0.33	3	9	1	0.33
C4	1	0.33	3	1	5	7	0.33	0.33
C5	0.33	0.2	0.33	0.2	1	3	0.2	0.2
C6	0.11	0.14	0.11	0.14	0.33	1	0.11	0.2
C7	1	1	1	3	5	9	1	3
C8	0.33	0.33	3	3	5	5	0.33	1

** C1, …, and C8 are the criteria already explained in Chapter 3

Table 4.7: Results for pairwise comparison between criteria scenario 2 (decision criteria matrix)

Criteria for Selection	C1	C2	C3	C4	C5	C6	C7	C8
C1	1	2	4	1	3	0.25	1	3
C2	0.5	1	4	3	2	0.2	0.33	0.5
C3	0.25	0.25	1	0.33	2	0.14	0.2	0.33
C4	1	0.33	3	1	3	0.14	0.2	2
C5	0.33	0.5	0.5	0.33	1	0.33	0.2	2
C6	4	5	7	7	3	1	1	5
C7	1	3	5	5	5	1	1	3
C8	0.33	2	3	0.5	0.5	0.2	0.33	1

** C1, …, and C8 are the criteria already explained in Chapter 3

Table 4.8: Results for comparison between criteria for scenario 3 (decision criteria matrix)

Criteria for Selection	C1	C2	C3	C4	C5	C6	C7	C8
C1	1	2	4	1	3	0.25	1	3
C2	0.50	1	4	3	2	0.20	0.33	0.50
C3	0.25	0.25	1	0.33	2	0.14	0.2	0.33
C4	1	0.33	3	1	3	0.14	0.2	2
C5	0.33	0.5	0.5	0.33	1	0.33	0.2	2
C6	4	5	7	7	3	1	1	5
C7	1	3	5	5	5	1	1	3
C8	0.33	2	0.5	0.5	0.2	0.2	0.33	1

** C1, …, and C8 are the criteria already explained in Chapter 3

The consistency factor of the decision criteria matrix was further determined to validate the accuracy of the developed decision criteria matrix. With 8 criteria considered in the study, a value of 1.48 was selected as the Random Index (Saaty, 2000). Finally, a Consistency Ratio of 0.09 for scenario1, 0.08 for scenario 2 and -0.73 for scenario 3 was determined which means that the decision criteria matrix for the study is consistent. That is, the weights allocated for the various criteria are clearly defined. These results are in consonant to studies by several researchers who applied AHP in the attainment of various specific goals (Jorge *et al.*, 2015 and Aşchilean *et al.*, 2017).

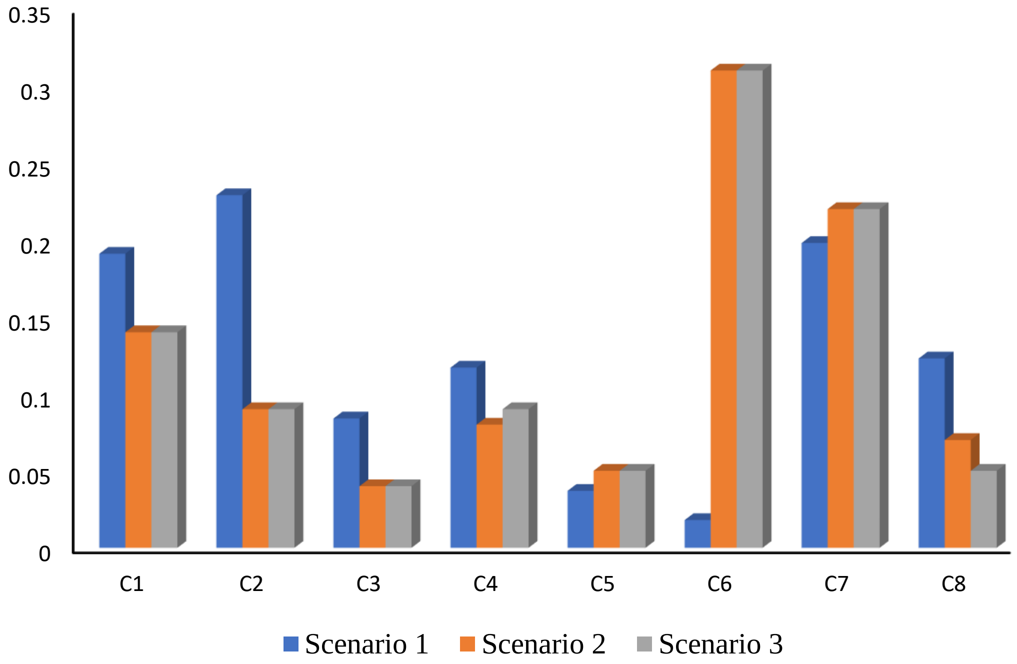

Figure 4.20: Significance of criteria after AHP evaluation for the three scenarios

4.6.1 Fuzzy logic

The vagueness that occurs during judgments were confronted by subsequently introducing fuzziness to the process. The weights obtained during the AHP methodology above were reconstructed to Table 4.9, 4.10 and 4.11 using linguistic variables and their corresponding TFNs.

Table 4.9: Linguistic and fuzzy weights of Scenario 1

C_1	C_2		$C_4 C_3$	C_5	C_6	C_7	C_8
H	VH	ML	M	L	VL	H	MH
0.7,0.9,1	0.9,1,1	0.1,0.3,0.5	0.3,0.5,0.7	0, 0.1, 0.3	0,0,0.1	0.7,0.9,1	0.5,0.7,0.9

Table 4.10: Linguistic and fuzzy weights of Scenario 2

C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
H	VH	ML	M	L	VL	H	MH
0.5,0.7,0.9	0.3,0.5,0.7	0.1,0.3,0.5	0.3,0.5,0.7	0, 0.1, 0.3	0.9,1,1	0.7,0.9,1	0.1,0.3,0.5

Table 4.11: Linguistic and fuzzy weights Scenario 3

C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
H	VH	ML	M	L	VL	H	MH
0.7,0.9,1	0.9,1,1	0.1,0.3,0.5	0.3,0.5,0.7	0, 0.1, 0.3	0,0,0.1	0.7,0.9,1	0.5,0.7,0.9

4.6.2 Ranking of alternatives

Fuzzy TOPSIS was introduced after the criteria weighting above allows the ranking of interval data. This method is based on different utility functions, and thus enables assessment of alternatives against multiple criteria in an integrated manner. Criteria that are necessary for performance rankings of digester configuration systems were determined from the literature and justified with the scenario planning tool. However, it has not been possible to apply all of these twelve criteria in the selection of the Anaerobic Digester systems. Nine criteria that can be obtained from the parameter were found after spotting the casual links between the twelve criteria. It is possible to use expert opinion for the criteria for which data cannot be obtained. However, this study analyzed quantitative data only, without recourse to expert opinion. The Fuzzy TOPSIS allowed the ranking of interval data to convert the qualitative data into linguistic variables and subsequently to numbers. Using MCDA techniques, suitable Anaerobic digesters were selected from a list of potential alternatives as showed in the subsequent sections. The developed list of driving forces (criteria for selection) that contributes to the selection of Anaerobic digesters alongside a summary of their attributes is presented in Chapter 3. Table 4.11 illustrates the fuzzy linguistic terms employed to determine the importance of attributes and the rating of alternative anaerobic digesters according to the parameters.

Table 4.12: The linguistic variables for scenario 1

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	G	G	VG	G	MP	MG	MG	G
A_2	VG	G	G	VG	VG	F	G	MG
A_3	F	VG	G	VG	G	VG	VG	G
A_4	VG	MG	G	VG	VG	MP	G	VG
A_5	P	P	G	VG	VG	P	MG	G
A_6	G	G	G	G	F	VG	MG	VG
A_7	VG	VG	G	G	G	G	MG	G

Table 4.13: The linguistic variables for scenario 2

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	G	G	VG	VG	G	MP	MG	G
A_2	VG	VG	G	VG	G	VG	MP	MP
A_3	F	G	G	G	G	P	F	VG
A_4	VG	MG	G	VG	VG	MP	G	VG
A_5	P	F	G	VG	F	G	VG	P
A_6	VG	G	MG	G	F	VG	VG	VG
A_7	VG	G	G	VG	F	G	G	VG

Table 4.2: The linguistic variables for scenario 3

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	G	G	VG	VG	G	MP	MG	G
A_2	VG	VG	VG	VG	G	VG	MP	MP
A_3	G	MG	MG	G	VG	F	G	VG
A_4	VG	MG	G	VG	VG	MP	G	VG
A_5	G	P	MG	VG	VG	MG	MP	G
A_6	VG	G	G	VG	F	VG	G	VG
A_7	VG	F	G	G	G	VG	MG	G

Fuzzification process, in this case, shows the performance of anaerobic digesters within the fuzzy neighborhood as shown in Table 4.9, the result shown is in crisp numerical figures which were changed into fuzzy equivalences within the possible interval [0, 1]. Equation (3.12) was used for these calculations, a classical demonstration of this step was seen the membership function (7,9,10) is a set of positive fuzzy triangular numbers which represents a decision of Good (G) for COD/VS reduction efficiency criteria 1(C_1) in the case of Anaerobic fluidized bed reactor alternative 1(A1). The same process is repeated for all the alternatives and their criteria in each scenario respectively. Hence, the fuzzy numbers of each criteria due to screened alternatives and scenarios which illustrates the original assessment information.

Table 4.15: Set of fuzzy numbers developed for scenario 1

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	7,9,10	7,9,10	9,10,10	9,10,10	7,9,10	1,3,5	5,7,9	7,9,10
A_2	9,10,10	7,9,10	7,9,10	9,10,10	9,10,10	3,5,7	7,9,10	5,7,9
A_3	3,5,7	9,10,10	7,9,10	9,10,10	7,9,10	9,10,10	9,10,10	7,9,10
A_4	9,10,10	5,7 9	7,9,10	9,10,10	9,10,10	1,3,5	7,9,10	9,10,10
A_5	0,1,3	0,1,3	7,9,10	9,10,10	9,10,10	0,1,3	5,7,9	7,9,10
A_6	7,9,10	7,9,10	7,9,10	7,9,10	3,5,7	9,10,10	5,7,9	9,10,10
A_7	9,10,10	9,10,10	7,9,10	7,9,10	7,9,10	7,9,10	5,7,9	7,9,10

Table 4.16: Set of fuzzy triangular numbers developed for scenario 2

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	7,9,10	7,9,10	9,10,10	9,10,10	7,9,10	1,3,5	5,7,9	7,9,10
A_2	9,10,10	9,10,10	7,9,10	9,10,10	7,9,10	9,10,10	1,3,5	1,3,5
A_3	3,5,7	7,9,10	7,9,10	7,9,10	7,9,10	0,1,3	3,5,7	9,10,10
A_4	9,10,10	5,7 9	7,9,10	9,10,10	9,10,10	1,3,5	7,9,10	9,10,10
A_5	0,1,3	3,5,7	7,9,10	9,10,10	3,5,7	7,9,10	9,10,10	0,1,3
A_6	9,10,10	7,9,10	5,7,9	7,9,10	3,5,7	9,10,10	9,10,10	9,10,10
A_7	9,10,10	7,9,10	7,9,10	9,10,10	3,5,7	7,9,10	7,9,10	9,10,10

Table 4.17:l Set of fuzzy triangular numbers developed for scenario 3

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	7,9,10	7,9,10	9,10,10	9,10,10	7,9,10	1,3,5	5,7,9	7,9,10
A_2	9,10,10	9,10,10	9,10,10	9,10,10	7,9,10	9,10,10	1,3,5	1,3,5
A_3	7,9,10	5,7 9	5,7 9	7,9,10	9,10,10	3,5,7	7,9,10	9,10,10
A_4	9,10,10	5,7 9	7,9,10	9,10,10	9,10,10	1,3,5	7,9,10	9,10,10
A_5	7,9,10	0,1,3	5,7,9	9,10,10	9,10,10	5,7,9	1,3,5	7,9,10
A_6	9,10,10	7,9,10	7,9,10	9,10,10	3,5,7	9,10,10	7,9,10	9,10,10
A_7	9,10,10	3,5,7	7,9,10	7,9,10	7,9,10	9,10,10	5,7,9	7,9,10

Also, the fuzzy normalized and weighted normalized decision matrix constructed in tabl 4.17 shows the result of the weighted normalized fuzzy decision matrix as defined in equation (13) and (14). The matrix obtained was used to change the crisp result obtained for different alternative anaerobic digesters to evaluate the best option by the triangular fuzzy numbers within the interval [0, 1].

Table 4.18: The aggregated weighted and normalized matrix fuzzy decision matrix of alternatives (Scenario 1)

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	0.49,0.81,1	0, 0, 0	0.01,0.033,0.055	0.27,0.5,0.7	0,0.011,0.042	0, 0, 0	0.35,0.63,0.9	0.35,0.63,0.9
A_2	0.63,0.9,0.1	0, 0, 0	0.01,0.033,0.07	0.27,0.5,0.8	0,0.011,0.033	0, 0, 0	0.49,0.81,1	0.25,0.63,0.81
A_3	0.21,0.45,0.7	0, 0, 0	0.01,0.033,0.07	0.27,0.5,0.9	0,0.011,0.042	0, 0, 0	0.63,0.9,1	0.35,0.63,0.9
A_4	0.63,0.9,0.1	0, 0, 0	0.01,0.033,0.07	0.27,0.5,0.10	0,0.011,0.033	0, 0, 0	0.49,0.81,1	0.45,0.7,0.9
A_5	0,0.09,0.3	0, 0, 0	0.01,0.033,0.07	0.27,0.5,0.11	0,0.011,0.033	0, 0, 0	0.35,0.63,0.9	0.35,0.63,0.9
A_6	0.49,0.81,1	0, 0, 0	0.01,0.033,0.07	0.27,0.45,0.7	0,0.020,0.099	0, 0, 0	0.35,0.63,0.9	0.45,0.7,0.9
A_7	0.63,0.9,0.1	0, 0, 0	0.01,0.033,0.07	0.27,0.45,0.8	0,0.011,0.042	0, 0, 0	0.35,0.63,0.9	0.35,0.63,0.9
A^*	**0.49,0.81,1**	**0,0,0**	**0.01,0.033,0.055**	**0.27,0.5,0.9**	**0,0.011,0.033**	**0,0,0**	**0.63,0.9,1**	**0.45,0.7,0.9**
A^-	**0,0.09,0.3**	**0.099,0.14,0.2**	**0.01,0.033,0.07**	**0.27,0.5,0.10**	**0,0.020,0.099**	**0.1,0.1,0.11**	**0.35,0.63,0.9**	**0.25,0.63,0.81**

Table 4.19: The aggregated weighted and normalized matrix fuzzy decision matrix of alternatives (Scenario 2)

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	0.35,0.63,0.1	0.03,0.055,0.098	0,0,0.011	0.27,0.5,0.7	0, 0.011, 0.042	0.9,0.33,0.2	0.077,0.126,0.2	0.07,0.27,0.5
A_2	0.45,0.7,0.9	0.03,0.03,0.088	0,0,0.014	0.27,0.5,0.7	0, 0.011, 0.042	0.81,1,1	0.14,0.0297,0.1	0.01,0.09,0.1
A_3	0.15,0.35,0.6	0.03,0.055,0.098	0,0,0.014	0.27,0.45,0.7	0, 0.011, 0.042	0,0.1,0.33	0.098,0.19,0.33	0.09,0.3,0.5
A_4	0.45,0.7,0.9	0.033,0.055,0.020	0,0,0.014	0.27,0.5,0.7	0, 0.01, 0.033	0.9,0.33,0.2	0.07,0.099,0.14	0.09,0.3,0.5
A_5	0,0.07,0.27	0.042,0.1,0.077	0,0,0.014	0.27,0.5,0.7	0, 0.02, 0.099	0.63,0.9,1	0.07,0.09,0.11	0,0.03,0.165
A_6	0.45,0.7,0.9	0.03,0.055,0.098	0,0,0.09	0.27,0.45,0.7	0, 0.02, 0.099	0.81,1,1	0.07,0.09,0.11	0.09,0.3,0.5
A_7	0.45,0.7,0.9	0.03,0.055,0.098	0,0,0.014	0.27,0.5,0.7	0, 0.02, 0.099	0.63,0.9,1	0.07,0.099,0.14	0.09,0.3,0.5
A^*	**0.45,0.7,0.9**	**0.03,0.055,0.098**	**0,0,0.09**	**0.27,0.45,0.7**	**0, 0.01, 0.033**	**0.81,1,1**	**0.07,0.09,0.11**	**0.09,0.3,0.5**
A^-	**0,0.07,0.27**	**0.03,0.03,0.088**	**0,0,0.014**	**0.27,0.5,0.7**	**0, 0.02, 0.099**	**0,0.1,0.33**	**0.098,0.19,0.33**	**0,0.03,0.165**

Table 4.20: The aggregated weighted and normalized matrix fuzzy decision matrix of alternatives (Scenario 3)

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	0.21,0.25,0.7	0.07,0.27,0.5	0.1,0.11,0.14	0.09,0.3,0.5	0,0.011,0.042	0.14,0.297,0.1	0.45,0.7.0.9	0,0.09,0.3
A_2	0.27,0.5,0.7	0.09,0.3,0.5	0.1,0.11,0.011	0.09,0.3,0.5	0,0.011,0.042	0.07,0.09,0.11	0.09,0.3,0.5	0,0.03,0.15
A_3	0.21,0.45,0.7	0.05,0.27,0.45	0.1,0.11,0.02	0.07,0.27,0.5	0,0.1,0.3	0.098,0.18,0.33	0.63,0.9,1	0,0.1,0.3
A_4	0.27,0.5,0.7	0.05,0.27,0.46	0.1,0.11,0.017	0.09,0.3,0.5	0,0.1,0.3	0.14,0.297,0.1	0.63,0.9,1	0,0.1,0.3
A_5	0.21,0.45,0.7	0,0.03,0.15	0.1,0.11,0.02	0.09,0.3,0.5	0,0.1,0.3	0.077,0.126,0.2	0.09,0.3,0.5	0,0.09,0.3
A_6	0.27,0.5,0.7	0.07,0.27,0.5	0.1,0.11,0.014	0.09,0.3,0.5	0,0.020,0.099	0.07,0.09,0.11	0.63,0.9,1	0,0.1,0.3
A_7	0.27,0.5,0.7	0.03,0.15,0.35	0.1,0.11,0.014	0.07,0.27,0.5	0,0.011,0.042	0.07,0.09,0.11	0.45,0.7,0.9	0,0.09,0.3
A^*	**0.27,0.5,0.7**	**0.09,0.3,0.5**	**0.1,0.11,0.011**	**0.09,0.3,0.5**	**0,0.011,0.042**	**0.07,0.09,0.11**	**0.63,0.9,1**	**0,0.1,0.3**
A^-	**0.21,0.45,0.7**	**0,0.03,0.15**	**0.1,0.11,0.02**	**0.07,0.27,0.5**	**0,0.1,0.3**	**0.14,0.297,0.1**	**0.09,0.3,0.5**	**0,0.03,0.15**

The distance of the performance value obtained in this step to the ideal distance gave the similarity coefficient and ranking order of the anaerobic digesters using Equation (15), Equation (16) and Equation (17) respectively. The distances were on both sides; thus, one side was the FPIS as seen in Table, and the other side was also defined as the FNIS. The table is a representation of FNIS as illustrated below for A1 and C1 in the case of scenario1.

$$A^{*} = \sqrt{\frac{1}{3}(0.49-0.49)^2 + (0.81-0.81)^2 + (1-1)^2} = 0.$$

$$A^{-} = \sqrt{\frac{1}{3}(0.49-0)^2 + (0.81-0.09)^2 + (1-0.3)^2} = 0.6036.$$

Table 4.21: FPIS ($A*$) for scenario 1

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	0.0000	0.5214	0.0000	0.1156	0.0052	0.0578	0.2319	0.0705
A_2	0.5284	0.5224	0.0087	0.0578	0.0000	0.1155	0.0960	0.1329
A_3	0.2425	0.5247	0.0087	0.0000	0.0052	0.0064	0.0000	0.0705
A_4	0.5284	0.5115	0.0087	0.4619	0.0000	0.0000	0.0961	0.0000
A_5	0.6451	0.0016	0.0087	0.4561	0.0000	0.1034	0.2319	0.0705
A_6	0.0000	0.5202	0.0087	0.1190	0.0385	0.0528	0.2319	0.0000
A_7	0.5288	0.7267	0.0087	0.0645	0.0052	0.0577	0.2319	0.0705

Table 4.22 FPIS ($A*$) for scenario 2

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	0.4672	0.0000	0.0502	0.0289	0.0052	0.6047	0.0561	0.1160
A_2	0.0000	0.0155	0.0485	0.0289	0.0052	0.0000	0.0542	0.2626
A_3	0.3084	0.0000	0.0485	0.0000	0.0052	0.7989	0.1405	0.0000
A_4	0.0000	0.0450	0.0485	0.0289	0.0006	0.6047	0.0181	0.0000
A_5	0.5759	0.0295	0.0485	0.0289	0.0385	0.1189	0.0000	0.2538
A_6	0.0000	0.0000	0.0456	0.0000	0.0385	0.0000	0.0000	0.0000
A_7	0.0000	0.0000	0.0485	0.0289	0.0385	0.1189	0.5199	0.0000

Table 4.23: FPIS ($A*$) for scenario 3

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	0.1484	0.0208	0.0017	0.0000	0.0000	0.1263	0.1657	0.0058
A_2	0.0000	0.0000	0.0577	0.0000	0.0000	0.0000	0.5482	0.0956
A_3	0.0451	0.0408	0.0052	0.0208	0.1489	0.1381	0.0000	0.1633
A_4	0.0000	0.0370	0.0035	0.0000	0.1490	0.1263	0.0000	0.1633
A_5	0.0451	0.2604	0.0052	0.0000	0.1490	0.0561	0.5482	0.0059
A_6	0.0000	0.1580	0.00173	0.0000	0.0329	0.0115	0.0000	0.1633
A_7	0.0000	0.1273	0.0017	0.0208	0.0000	0.0115	0.1657	0.00587

Table 4.24: The distance between each criterion and FNIS ($A-$) for scenario 1

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	0.6451	0.0390	0.0087	0.3097	0.0333	0.08185	0.0000	0.0777
A_2	0.6036	0.0341	0.0087	0.4041	0.4041	0.0968	0.1438	0.0000
A_3	0.3335	0.0571	0.0087	0.4619	0.0333	0.0816	0.2319	0.0777
A_4	0.6036	0.0052	0.0087	0.0000	0.0385	0.0816	0.4803	0.1329
A_5	0.0000	0.5113	0.0087	0.0058	0.0385	0.1034	0.0000	0.0777
A_6	0.6451	0.0391	0.0087	0.3476	0.0000	0.0000	0.0000	0.1329
A_7	0.6036	0.0571	0.0087	0.4051	0.0333	0.4714	0.0000	0.0777

Table 4.25; The distance between each criterion and FNIS ($A-$) for scenario 2

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	0.1409	0.0155	0.0173	0.0000	0.0615	0.5415	0.0845	0.2413
A_2	0.5670	0.0000	0.0000	0.0000	0.0615	0.7956	0.1639	0.0796
A_3	0.3935	0.0155	0.0000	0.0289	0.0615	0.0000	0.0000	0.2538
A_4	0.6737	0.0419	0.0000	0.0000	0.0599	0.5415	0.4750	0.2538
A_5	0.1403	0.0415	0.0000	0.0000	0.0000	0.6027	0.4793	0.1559
A_6	0.1403	0.0155	0.0289	0.0289	0.0000	0.7989	0.4793	0.2002
A_7	0.1403	0.0155	0.0000	0.0000	0.0000	0.7038	0.4750	0.2538

Table 4.25 The distance between each criterion and FNIS ($A-$) for scenario 3

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	0.0451	0.2483	0.0346	0.0208	0.1576	0.0000	0.3871	0.0932
A_2	0.0451	0.2604	0.0519	0.0208	0.1576	0.1263	0.0000	0.0000
A_3	0.0451	0.2239	0.1039	0.0000	0.0000	0.1509	0.5482	0.0956
A_4	0.0451	0.2282	0.1057	0.0208	0.0000	0.0000	0.5482	0.0956
A_5	0.0451	0.0000	0.1039	0.0208	0.0000	0.1200	0.0000	0.0932
A_6	0.0451	0.2483	0.0346	0.0208	0.1249	0.1263	0.5482	0.0957
A_7	0.0451	0.1358	0.0346	0.0208	0.1576	0.1263	0.3871	0.0933

Finally, the closeness coefficient of every alternative anaerobic digester was calculated and Fig shows the results of the preferred digesters. The result becomes notably closer to the FPIS and further from the FNIS as CCi approaches 1. Therefore, according to the closeness coefficient, the ranking order of all anaerobic digesters gave the best option among the seven alternative anaerobic digesters. The closeness coefficients obtained were used ranking order of the anaerobic digesters in all three scenarios based as shown in Table 8.

Table 4.26: Importance ranks according to fuzzy AHP-TOPSIS method for scenario 1

	S^+	S^-	$S^+ + S^-$	$\frac{S^-}{S^+ + S^-}$	Rank	Digester
A_1	1.0023	1.1954	2.1976	0.5439	3	AFBR
A_2	1.4612	1.6953	3.1564	0.5371	4	APFR
A_3	0.8579	1.2857	2.1436	0.5998	1	EGSB
A_4	1.6065	1.3509	2.9575	0.4568	6	ICR
A_5	1.5172	0.7453	2.2626	0.3294	7	UASB
A_6	0.9709	1.1734	2.1443	0.5472	2	ABR
A_7	1.6940	1.6569	3.3509	0.4945	5	AF

Table 4.27: Importance ranks according to fuzzy AHP-TOPSIS method for scenario 2

	S^+	S^-	$S^+ + S^-$	$\frac{S^-}{S^+ + S^-}$	Rank	Digester
A_1	2.3018	1.9098	4.2107	0.4536	6	AFBR
A_2	0.7177	2.8883	3.6060	0.8007	2	UPFR
A_3	2.254	1.3046	3.5589	0.3665	7	EGSB
A_4	1.2918	3.5433	4.8351	0.7328	3	ICR
A_5	1.8948	2.4588	4.3538	0.5648	5	UASB
A_6	0.1453	3.8547	4.0004	0.9526	1	ABR
A_7	1.30715	3.6750	4.9821	0.6779	4	AF

Table 4.28: Importance ranks according to fuzzy AHP-TOPSIS method for scenario 3

	S^+	S^-	$S^+ + S^-$	$\frac{S^-}{S^+ + S^-}$	RANK	DIGESTERS
A_1	0.8119	1.7093	2.5212	0.6779	4	AFBR
A_2	1.1150	1.1469	2.2619	0.4856	6	APFR
A_3	0.9740	1.9439	2.9179	0.6662	5	EGSB
A_4	0.8296	1.8074	2.6371	0.6854	3	ICR
A_5	1.8529	0.5855	2.4384	0.2401	7	UASB
A_6	0.6366	2.1544	2.7909	0.7719	1	ABR
A_7	0.5766	1.7331	2.3096	0.7503	2	AF

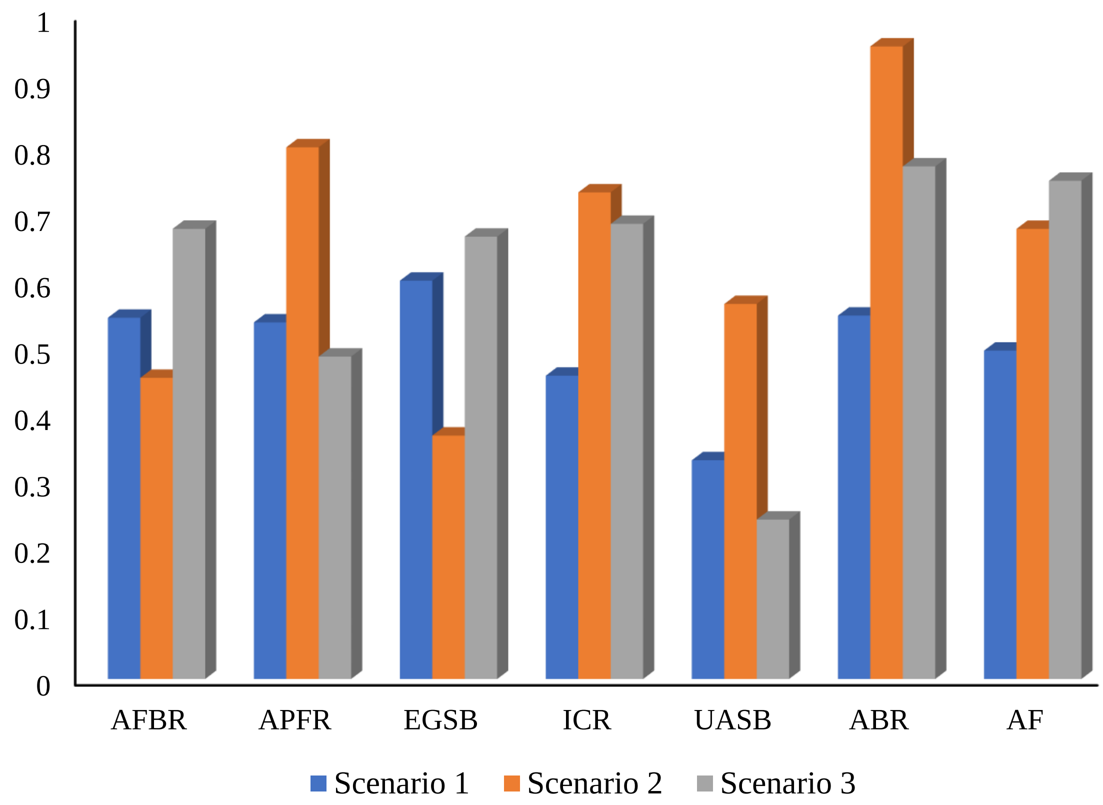

Figure 4.21 Results of mcda selection process

The results of the MCDA show that the EGSB reactor was the best alternative for scenario 1. This is a high rate reactor and therefore confirms the statement made in (Vladimir *et al.*, 2015) that the focus of high rate digester is not on energy production, but instead on treating biodegradable wastes efficiently and economically thus and it prioritizes environmental sanitation. These digesters rarely have a positive energy balance. The ranking of anaerobic digesters with regard to criteria performance for scenario 3 is as follows: ABR > AF > ICR >AFBR > EGSB.> APFR> UASB. Same was repeated for scenario 2. This means that the ABR out-performed all of the seven anaerobic digesters considered for scenario 3. These results show the impact of the comprehensive operational conditions of ABR in the treatment of waste for nutrients recovery for farmlands; this anaerobic digester distinguished itself from the other digesters by its high treatment efficiency, such as offering high-quality COD/VS reduction efficiency, minimizing total solid content present in digestate after the digestion process, high organic loading capacity, demonstrating high standards of thermal stability and ability to maximize the retention of residual nutrients. For a typical case of treating waste for the purpose of agricultural nutrient recovery, the

ABR digester has a stronger ability to resist shock loads and also perform better under ambient conditions. These operational conditions of the ABR digester made it the most preferred digester in the ranking stage. The case of scenario 1 and Scenario 2, the EGSB and Anaerobic baffled reactor were the digesters with highest ranks based on their performance in the criteria taking into consideration the objective of each criterion and scenario in mind as stated in Chapter three.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The following conclusions were made after the study.

5.1.1. Waste quantification and characterization

The experimental records of the cumulative biogas production from pig waste, abattoir waste, food waste and pineapple waste were obtained. The data was used for the AR optimization process.

5.1.2. Generalized digester structure

Two-dimensional attainable regions was produced for the optimal reactor configurations for both continuous and batch operation schedules. The four configurations produced differ for each digested substrate. The configurations produced were made up of digesters operated in a continuous (axial mixing) and/or plug flow (no axial mixing) mode. For the batch operations, the required configurations for the abattoir and pig waste were three CSTRs whiles the pineapple and food waste make use of four CSTRs respectively. Also, for the continuous operation schedules configurations, abattoir and pig waste were made up of one CSTR and one PFR. The food and pineapple waste were also made up of two CSTRs and one PFR. The application of AR to this study has however validated the view of Neba *et al.* (2019) which states that 'configurations of any new substrate can be developed from AR' as presented this research.

5.1.3. Selection of digester subunit

A systematic methodological framework for the selection of Anaerobic Digesters has been presented. The framework presents a systematic way of selecting anaerobic digesters and reduces the uncertainties and ambiguity related to the selection of anaerobic digester for a subunit. The methodology presented here is a well-organized, strategic decision supporting tool for decision-makers and planners.

5.2 RECOMMENDATIONS

The following recommendations were made:

5.2.1. Optimal digester structure

The decision support system could be embedded in a software that can be used for rapid selection of digesters by the industries and individuals.

5.2.2. Selection of digester subunit

It would be interesting to construct and assess the performance of the proposed configurations in this study through further research.

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