EXPERIMENTAL INVESTIGATION OF UPFLOW BIOREACTORS WITH CENTRAL SUBSTRATE DISPENSER

BY

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CERTIFICATION

This is to certify that Ononogbo Chibuike (20094735588) of the Department of Mechanical Engineering, Federal University of Technology, Owerri carried out this work as an original research work and that this work satisfies in part, the requirement for the award of the Degree of Master's of Engineering (M. Eng) in Mechanical Engineering (Energy and Power), Federal University of Technology, Owerri.

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DEDICATION

This research work is dedicated to the Most Blessed Trinity, Father, Son and Holy Ghost for the wonderful graces and courage I received to be able to undertake and complete this work in good health.

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ABBREVIATIONS AND NOMENCLATURE

AD – Anaerobic Digestion

AFBR – Anaerobic Fluidized –Bed Reactor

B –Biogas Yield

B_{max} – Biogas Potential, ml

B_t – Cummulative Biogas Production with time, ml/day

BOD – Biological Oxygen Demand

BPLP – Biogas Production Lag Phase

CISTR – Continuous Ideally Stirred - Tank Reactor

C/N – Carbon/Nitrogen ratio of substrate

COD – Chemical Oxygen Demand, mg/l

CSD – Central Substrate Dispenser

CSTR – Continuous Stirred - Tank Reactor

GHG – Green House Gas

GTZ – German Technical Cooperation Agency

GWP – Global Warming Potential

HRT – Hydraulic Retention Time

HS – High Solids, mg/l

IEA – International Energy Agency

ISAT – Information and Advisory Services on Appropriate Technology

$\boldsymbol{K}$ **–** First Order Kinetic Constant

$\boldsymbol{K_S}$ **–** Rate Constant

LS – Low Solids, mg/l

MS – Medium Solids, mg/l

MSW – Municipal Solid Waste

NFFO – Non- Fossil Fuel Obligation

OLR – Organic Loading Rate

OMW – Organic Municipal Waste

Q – Volumetric Feed Flow Rate, l/day

$\mathbf{R_b}$ **–** Rate of Production of Biogas, ml/day

RISE-AT –Regional Information Service Center for Southeast Asia on Appropriate Technology

S – Substrate Concentration, g/l

$\mathbf{S_O}$ **–** Initial Substrate Concentration, g/l

t – Retention (residence) Time, h

TS – Total Solids, mg/l

UAFP – Upflow Anaerobic Filter Process

UASB – Upflow Anaerobic Sludge Blanket Reactor

UB – Upflow Bioreactor

UBCSD – Upflow Bioreactor with Central Substrate Dispenser

V – Substrate Velocity

VS – Volatile Solid, mg/l

WW II – World War II

$\mathbf{Y_M}$ **–** Methane Yield, g/g

$\boldsymbol{\lambda}$**–** Biogas Production Lag Time, days

ABSTRACT

Experimental investigation of anaerobic digestion of the organic fraction of municipal solid waste (MSW) in an upflow bioreactor with central substrate dispenser (UBCSD) is presented. The UBCSD consists of two similar size bioreactors joined by a central substrate dispenser (CSD). The UBCSD is a component of an integrated system of bioreactors also containing the upflow anaerobic sludge blanket (UASB) reactor and the continuous stirred tank reactor (CSTR), assembled systematically to achieve desired results. The UASB has an internal volume of 76litres, the UBCSD, 64.8litres and the CSTR, 76litres, respectively. The UBCSD utilized a CSD as its inherent feature to help generate an up-flow, down-flow and cross-flow pattern of the working substrate during its operation with a view to enhancing substrate mixing effectiveness. These reactors were fed with the slurry and allowed to run without interruption for a period of 10-days hydraulic retention time (HRT) at a mesophilic temperature of 37^0 C. Biogas production for each reactor was recorded every six (6) hours while the chemical oxygen demand reduction was measured daily. The UBCSD generated the highest level of cumulative biogas production with the value of 52915 ml, while the UASB and CSTR yielded 23550 ml and 28980 ml, respectively. UBCSD also yielded the highest percentage COD removal of 95.2%, followed by the CSTR with a value of 80.8%; while the UASB yielded the lowest percentage COD removal of 79.0%. The values for the first order kinetic constant (***k***) of COD which is a measure of the rate at which the substrate COD is reduced for UBCSD, UASB and CSTR were obtained as 0.2857, 0.147 and 0.1708, respectively, based on the modified Fenton's first order model. With these results, it is deducible that the UBCSD is the most effective reactor amongst the three in terms of substrate stabilization and biogas production capacity. This is easily attributable to the central substrate dispenser for effective mixing of substrate during digestion.

Keywords: **anaerobic, biogas, bioreactor, chemical oxygen demand, digestion, retention time, substrate.**

CHAPTER ONE

INTRODUCTION

1.1 Background

According to Naught and Wilkson (1997), bioreactors are defined as any manufactured or engineered device that supports a biologically active environment. They are commonly cylindrical in configuration, ranging in size from a few liters to cubic meters, and are often made of stainless steel. The design of bioreactors is quite a complex engineering task. Under optimum conditions the microorganisms or cells will reproduce at an astounding rate. The vessel's environmental conditions like gas flowrates, temperature, pH, and agitation speed need to be closely monitored and controlled. One bioreactor manufacturer, Broadley-James Corporation, uses vessels, sensors, controllers, and a control system, digitally networked together for their bioreactor system.

Bioreactors generate biogas which originates from bacteria in the process of bio-degradation of organic materials under aerobic (with air) or anaerobic (without air) conditions. The natural generation of biogas is an important part of the biogeochemical carbon cycle. Methanogens (methane producing bacteria) are the last link in a chain of micro-organisms which degrade organic material and return the decomposition products to the environment. In this process biogas is generated, a source of renewable energy. Each year some 590-880 million tons of methane are released worldwide into the atmosphere through microbial activity. About 90% of the emitted methane derives from biogenic sources, i.e. from the decomposition of biomass. The remainder is of fossil origin (e.g. petrochemical processes). In the northern

hemisphere, the present tropospheric methane concentration amounts to about 1.65 ppm. (*ISAT, 2005).*

However, knowledge of the fundamental processes involved in methane fermentation is necessary for planning, building and operating bioreactors. Anaerobic fermentation involves the activities of three different bacterial communities. Biogas microbes consist of a large group of complex and differently acting microbe species, notable the methane-producing bacteria. The process of biogas-production depends on various parameters. For example, changes in ambient temperature can have a negative effect on bacterial activity. The classical work by O'Rourke (1968) showed the influence of temperature on the decrease of the volatile solids concentration of primary sludge in an anaerobic digester. Other parameters are:

- ❖ pH of substrate
- ❖ Waste Composition/Volatile Solids(VS)
- ❖ Carbon/Nitrogen ratio of substrate(C/N)
- ❖ Total Solids Content(TS)/Organic Loading Rate (OLR)
- ❖ Retention (or Residence) Time (RT)
- ❖ Flow / Mixing characteristics

In principle, all organic materials can ferment or be digested. However, only homogenous and liquid substrates can be considered for simple biogas plants: faeces and urine from cattle, pigs and possibly from poultry and the wastewater from toilets. When the plant is filled, the excrement has to be diluted with about the same quantity of liquid; if possible, the urine should be used. Waste and wastewater from food-processing industries are only suitable for simple plants if they are homogenous and in liquid form. The

maximum of gas-production from a given amount of raw material depends on the type of substrate.

Basically, the anaerobic biodegradation of organic material proceeds in the absence of oxygen and the presence of anaerobic microorganisms. Anaerobic digestion (AD) is the consequence of a series of metabolic interactions among various groups of microorganisms. It occurs in three stages, hydrolysis/liquefaction, acidogenesis and methanogenesis. The first group of microorganism secretes enzymes, which hydrolyses polymeric materials to monomers such as glucose and amino acids. These are subsequently converted by second group i.e. acetogenic bacteria to higher volatile fatty acids, H_2 and acetic acid. Finally, the third group of bacteria, methanogenic, convert H_2, CO_2, and acetate, to CH_4. The gas obtained during AD comprises of methane, carbon dioxide, some inert gases and sulfur compounds (Table 1.1). Usually 100-200 m3 of total gas are produced per ton of organic MSW digested (RISE-AT, 1998).

Well-functioning biogas systems can yield a whole range of benefits for their users, the society and the environment in general:

- production of energy (heat, light, electricity) ;
- transformation of organic waste into high quality fertilizer;
- improvement of hygienic conditions through reduction of pathogens, worm eggs and flies;
- reduction of workload, mainly for women, in firewood collection and cooking.
- environmental advantages through protection of soil, water, air and woody vegetation;

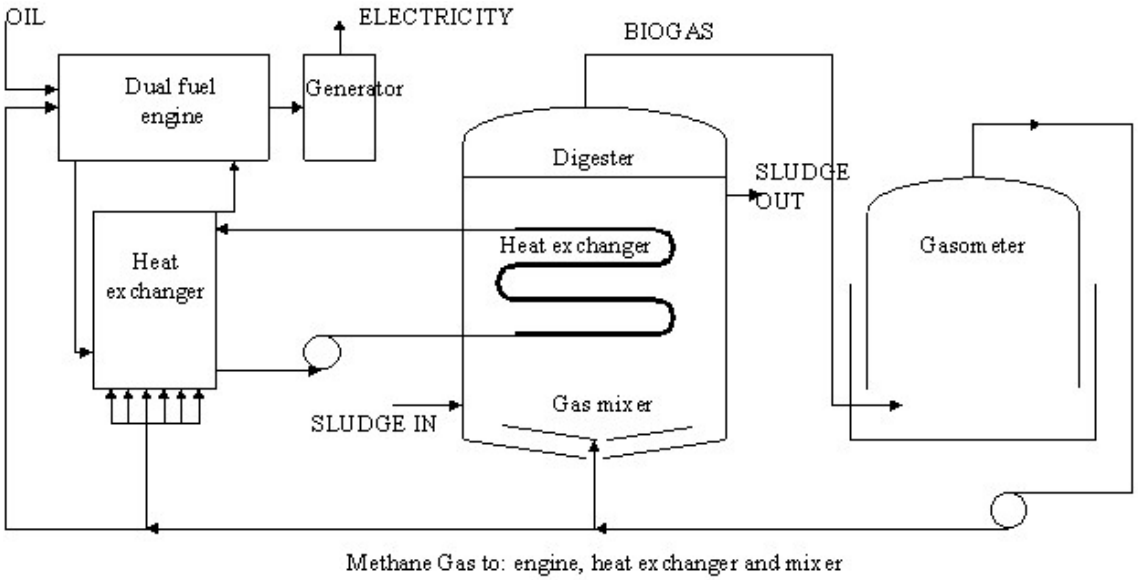
- micro-economical benefits through energy and fertilizer substitution, additional income sources and increasing yields of animal husbandry and agriculture;
- macro-economical benefits through decentralized energy generation, import substitution and environmental protection.

For some decades, the treatment of municipal solid waste (MSW) has been predominantly handled by the disposal of wastes in landfills sites. Using landfill approach for the treatment of wastes is oftentimes expensive and also causes land and underground water pollution. Landfills are the source of large emissions of methane to the atmosphere. Methane gas has a global warming potential (GWP) that is over twenty times that of carbon dioxide. Also, many utilities are very interested in earning credit for reducing green house gas (GHG) emissions. According to Verma et al., 2002 these utilities foresee the risk of mandatory GHG control imposed by future regulatory or legislative actions. Therefore, AD plants will be very attractive for utilities to earn GHG reduction credits.

According to Suzuki (1992), waste recycling plays a key role in the development of a sustainable economy. Therefore, the use of landfill approach for the treatment of wastes, should be considered an obsolete

technology. The classical approach, remediation without the production of recycled materials, does not contribute to durable material flows. Moreover, the production of reusable materials is a necessity to make waste treatment an attractive economic solution. For developing countries, the production of biogas and bio-fertilizer holds the promise of substituting increasing amounts of imported fossil fuels and mineral fertilizers. On an economic scale, the importance of digested sludge as a supplementary source of fertilizer is gradually gaining recognition. As populations continue to grow, there is a corresponding increase in the demand for food, fertilizers and energy. And a balance in this area can be achieved if anaerobic digestion (AD) technology is given the required level of consideration.

Generally, the overall AD process can be divided into four stages: Pretreatment, waste digestion, gas recovery and residue treatment. Most digestion systems require pre-treatment of waste to obtain homogeneous feedstock. The preprocessing involves separation of non-digestible materials and shredding. The waste received by AD digester is usually source separated or mechanically sorted. The separation ensures removal of undesirable or recyclable materials such as glass, metals, stones etc. In source separation, recyclables are removed from the organic wastes at the source. The waste is shredded before it is fed into the digester. Inside the digester, the feed is diluted to achieve desired solids content and remains in the digester for a designated retention time. For dilution, a varying range of water sources can be used such as clean water, sewage sludge, or re-circulated liquid from the digester effluent. A heat exchanger is usually required to maintain temperature in the digesting vessel (Figure 1.1).



Figigure 1.1 The flow diagram of low solid AD

(Ref: http://www.soton.ac.uk/~sunrise/anaerobicdig.htm#ADsolidwaste)

The biogas obtained in AD is scrubbed to obtain pipeline quality gas. In case of residue treatment, the effluent from the digester is dewatered, and the liquid recycled for use in the dilution of incoming feed. The biosolids are aerobically cured to obtain a compost product. As noted earlier, the AD systems treat various types of waste-streams and in some plants MSW is mixed with sewage sludge or other type of waste.

However, there are some technical problems associated with the conventional bioreactors. The major constraint is that of optimization of the

process parameters, especially the substrate mixing efficiency; and a considerable number of biogas plants have failed as a result. Unger et al (2000) showed that fluid flow and mixing have significant effect on the overall performance of the systems. So, in order to solve these flow and mixing problems associated with the conventional bioreactors, this research work will embark upon studying the flow characteristics of an upflow bioreactor with central substrate dispenser (UBCSD) and to investigate its performance relative to an upflow anaerobic sludge blanket reactor (UASB) and a continuous stirred tank reactor (CSTR).

1.2 Statement of Problem

Fluid flow/mixing efficiency is one of the most significant factors affecting reactor performance and scale-up requirements (Bonvillani et al. 2006). In the 27th Symposium conducted on Biotechnology for Fuels and Chemicals, it was shown that without mixing, reactor performance deteriorates in a short time, whereas with adequate mixing, continuous production of methane is observed in a longer period of time. Basically, one of the reasons for employing mixing in a digester is to blend the fresh material with digestate containing microbes. Furthermore, mixing prevents scum formation and avoids temperature gradients within the digester. Many

biogas plants today are not functioning satisfactorily, while some have gone out of operation due to low mixing efficiency. According to Agulannna (2012), some of the reactors reported to have failed in Nigeria are as listed below:

a. Cow dung biogas plant at May Flower Secondary School, Ikene, Ogun State.
b. The pig waste biogas plant at Ojokoro Cooperative Agricultural Society, Lagos.
c. Biogas plant at the University of Nigeria, Nsukka, etc.

The failure of these bioreactors is chiefly attributable to some technical problems, especially inappropriate substrate flow dynamics. But excessive mixing can disrupt the microbes, so, slow mixing is preferred. The kind of mixing equipment and amount of

mixing varies with the type of reactor and the solids content in the digester. Besides, since it is apparent that inadequate flow regime causes low performance of bioreactors, resulting in lower rates of biogas production; an improvement in slurry dynamics of bioreactors will, to a large extent help for the enhancement of bioreactor operations with attendant positive results. It is worthy of note that the rate of bacteriological methane production increases with temperature, the biodigestive performance could be inhibited or even reduced as a result. In general, unheated biogas plants perform satisfactorily only where mean annual temperatures are around 20^0C or above or where average daily temperature is at least 18^0C. Within the range of 20-30^0C mean temperature, gas production increases over-proportionately. If the temperature of the biomass is below 15^0C, gas production will be so slow that the biogas plant is no longer economically feasible. There are mainly two temperature ranges that provide optimum digestion conditions for the production of methane – the mesophilic and thermophilic ranges. The mesophilic range is between 20°C to 40°C and the optimum temperature is considered to be 30°C to 35°C. The thermophilic temperature range is between 50°C to 65°C (RISEAT, 1998). However, to achieve desired

goals, it is expected that a control system be incorporated into the bioreactor setup in order to help regulate the temperature of the heating elements so that the bioreactor operation will be carried out within the preset temperature ranges.

1.3 OBJECTIVES OF STUDY

Anaerobic digestion (AD) facilities generally have had a good record in treating a wide spectrum of waste streams like farm, industrial, and municipal wastes. Nevertheless, the earlier forms of bioreactors had considerably high problems due to lack of in-depth knowledge of the parameters which required considerations during their design and operations (Kale, 2003). However, following the progress in the development of bioreactors, a common problem of flow of the substrate is easily identified. Several works have been done to improve this phenomenon. The present work will introduce the upflow reactor into the reaction scheme with a central substrate dispenser to improve the flow of the resultant substrate. The overall goal of this study will be to perform extensive experimentation using

the upflow bioreactor with central substrate dispenser (UBCSD). The specific objectives include:

(i) Comparative studies of UBCSD in relation to the conventional upflow anaerobic sludge blanket (UASB) reactor and the continuous stirred tank reactor (CSTR).

(ii) Performance evaluation of UBCSD through extensive experimentation using organic municipal waste (OMW).

(iii) Determination of the biodegradation kinetic parameters using known kinetic model equations.

1.4 HYPOTHESIS OF STUDY

From the statement of problem, it is clear that success or failure of any bioreactor depends largely on the dynamics of the substrate. However, careful selection of other factors like: Biochemical requirements, Scale of operation as well as other Engineering factors are of great importance. So, having seen the importance of adequate flow and mixing of the fluid used for bioreactors and the regulation of other parameters like temperature, pH, COD, retention time, etc.; it can be postulated that the use of the central

substrate dispenser placed between two upflow bioreactors in order to enhance substrate flow, can in a significantly positive manner, influence the performance of the bioreactor of our interest.

1.5 JUSTIFICATION

Waste recycling plays a key role in the development of a sustainable economy (SUZUKI, 1992). Regrettably, over the years, municipal solid waste (MSW) treatment has been handled by dumping wastes in landfill sites. This method of municipal waste management however, has some attendant problems which most likely outweigh their envisaged advantages. Using landfill approach for the treatment of wastes is oftentimes expensive and also causes land and underground water pollution due to the presence in the wastes of some toxic substances. Landfills are the source of large emissions of methane to the atmosphere and methane gas has a global warming potential (GWP) that is over twenty times that of carbon dioxide. Also, many utilities are very interested in earning credit for reducing green house gas (GHG) emissions. It is obvious that these utilities foresee the risk of mandatory GHG control imposed by future regulatory or legislative actions. Therefore, AD plants will be very attractive for utilities to earn GHG reduction credits. In terms of environmental protection, biogas technology takes part in the global struggle against the greenhouse effect. It reduces the release of CO2 from burning fossil fuels in two ways. First, biogas is a direct substitute for gas or coal for cooking, heating, electricity generation and lighting. Additionally, the reduction in the consumption of artificial fertilizer avoids carbon dioxide emissions that would otherwise

come from the fertilizer producing industries. By helping to counter deforestation and degradation caused by overusing ecosystems as sources of firewood and by melioration of soil conditions biogas technology reduces CO2 releases from these processes and sustains the capability of forests and woodlands to act as a carbon sink. Anaerobic digestion has become an established and proven technology as a means of managing solid organic waste. However, it is worthy of note that many of the conventional anaerobic digestion systems have some recorded flow and mixing problems which to a large extent affect negatively their performances. However, the struggle to design bioreactor systems capable of solving these substrate flow problems associated with the existing reactors becomes more and more demanding. Hence this challenge informed the generation of an up-flow bioreactor with central substrate dispenser (UBCSD).

1.6 SCOPE OF STUDY

This work is geared towards studying the flow characteristics of the substrate [pre-treated Organic Municipal Waste (**OMW**)]. The chemical oxygen demand (**COD)** level of the effluent as an index of performance as well as the rate of methane production will be discussed. The experimental setup and processes will be considered. The results obtained from the experiment conducted on the **UBCSD** will be discussed in detail in relation to those obtained in a Continuous Stirred Tank Reactor (**CSTR**) and an

upflow anaerobic sludge blanket reactor (UASB) operating under the same conditions. Tables and graphs will be used for the analysis of the experimental results. The use of Matlab program will be employed to generate models for gas production and COD reduction.

CHAPTER TWO
LITERATURE REVIEW

2.1 BIODIGESTION/ BIOREACTOR ORIGIN AND DEVELOPMENT

Historical evidence indicates that the Anaerobic Digestion (AD) process is one of the oldest technologies. Biogas was used for heating bath water in Assyria during the 10th century BC and in Persia during the 16th century (www.biogasworks.com). Scientific interest in the manufacturing of gas produced by the natural decomposition of organic matter, was first reported in the seventeenth century by Robert Boyle and Stephen Hale, who noted that flammable gas was released by disturbing the sediment of streams and lakes. AD advanced with scientific research, and within the 17th century, Jan Baptista Van Helmont established that flammable gases evolved from decaying organic matter. In 1770, the Italian, Count Alessandro Volta collected marsh gas and investigated its burning behavior and in 1776, he showed that there was a relationship between the amount of decaying organic matter and the amount of flammable gas produced. In 1808, Sir Humphry

Davy determined that methane was present in the gases produced by cattle manure. He subsequently demonstrated the production of methane by the anaerobic digestion of cattle manure (Lusk, 1997). The first anaerobic digester was built by a leper colony in Bombay, India in 1859 and in 1884, Pasteur researched on biogas from animal residues. He proposed the utilization of horse litter to produce biogas for street-lighting. In 1895 the technology was developed in Exeter, England, where a septic tank [see fig.2.1] was used to generate gas for the sewer gas destructor lamp, a type of gas lighting. In the year 1904, further research work exercised following a definite knowledge of the performance of the septic tank, led to the installation of the first dual purpose tank for both sedimentation and sludge treatment in Hampton, England. In 1906, first anaerobic wastewater-treatment plant was designed in Germany and the following year, 1907, in Germany, a patent was issued for the Imhoff tank [see fig.2.2] an early form of digester. In 1913, the first anaerobic digester with heating facility was designed and in 1920 the first German sewage plant to feed the collected biogas into the public gas supply system was developed.

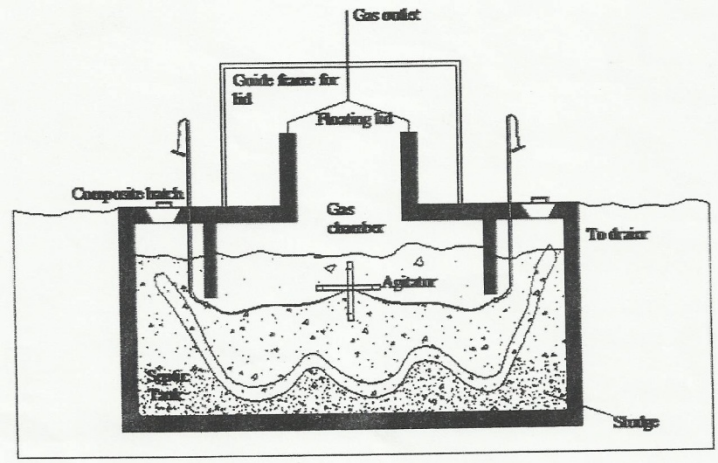


FIG. 2.1 SCHEMATIC OF THE SEPTIC TANK BIOGAS DIGESTER

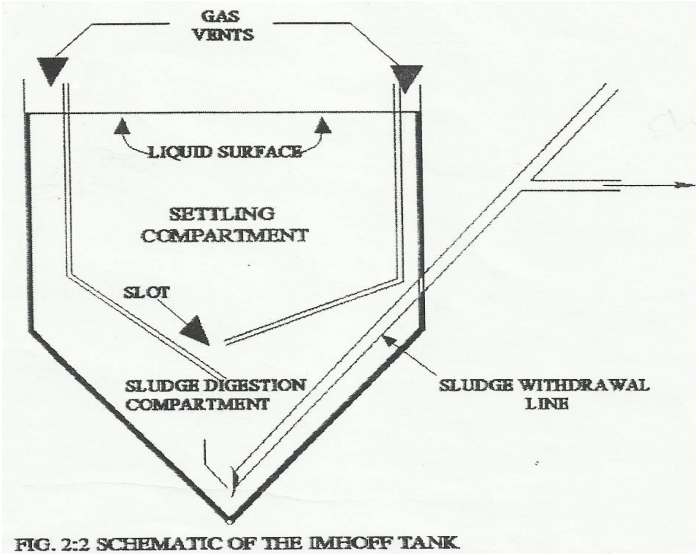


FIG. 2:2 SCHEMATIC OF THE IMHOFF TANK

Through scientific research, anaerobic digestion (AD) gained academic recognition in the 1930s. Further AD advances were due to the development of microbiology. Research led by Buswell and others (Lusk, 1997) in the 1930s identified anaerobic bacteria and the conditions that promote methane production. Further research was carried out to investigate the conditions under which methanogenic bacteria were able to grow and reproduce. This work was developed during World War II, during which in both Germany and France there was an increase in the application of anaerobic digestion for the treatment of manure. Prior to 1920, most of the AD took place in anaerobic ponds. As the understanding of AD process control and its benefits improved, more sophisticated equipment and operational techniques emerged. The result was the use of closed tanks and heating and mixing equipment to optimize AD. The primary aim of waste stabilization in due course led to the basic municipal sludge digester. This design then spread

throughout the world. However, methane production suffered a setback as low-cost coal and petroleum became abundant. AD systems made a comeback during WWII with fuel shortages hitting Europe but after the war AD was once again forgotten. Another factor that led to declining interest in AD was increased interest in aerobic digestion systems. While the developed world shunned AD except as a wastewater sludge digestion technique, developing countries such as India and China embraced this technology. These countries saw gradual increase in small-scale AD systems used mostly for energy generation and sanitation purpose. In the developed countries, industrial expansion and urbanization coupled with low-cost electricity resulted in aerobic composting and landfilling to become the choice technologies for waste treatment, until recent times. It is noteworthy

that the year 1940, met the discovery that addition of organic residues (fat) increases sewage gas production and in the year 1947, research demonstrated that the dung of one cow can give a hundred times more gas than the faeces of one urban inhabitant. In the year 1947 the first working group on biogas was established in Germany. In 1950, the installation of the first larger agricultural biogas plant was carried out and nearly 50 biogas plants were built, fed by litter mixed with water and dung. However, low oil prices and technical problems led to the shutdown of all but two plants. The energy crisis in 1973 and again in 1979 triggered renewed interest in development of simple AD systems for methane production as an energy source. India, China and Southeast Asia responded to the crisis with marked expansion of AD. Most of the AD systems were small digesters using combined human, animal and kitchen wastes. Many community digesters were installed to produce large volumes of biogas for village electrification. Also, Europe, North America and the Soviet Union became involved with research in AD for methane

production from animal manure. The U.S. established renewable energy programs, emphasizing the AD of biomass for energy production. The rush for deployment of AD systems to meet energy needs also led to many foreign-aid projects. Unfortunately, the knowledge on AD was still in a fledgling state and there were numerous failures. China, India and Thailand reported 50% failure rates. Failures of farm digesters in the U.S. approached 80%. Europe and Russia also experienced high farm digester failure rates (Lusk, 1997). Nevertheless, those designs that succeeded furthered the interest in research and development of AD. Apart from biogas production, AD found wider acceptance as an inexpensive technology for waste stabilization, nutrient recovery, reduction in biological oxygen demand (BOD), and sludge treatment. The dominant

application of AD technology has been in farm-based facilities. About six to eight million family-sized, lowtechnology digesters are used to provide biogas for cooking and lighting fuels with varying degrees of success. China and India have now adopted a trend towards larger, more sophisticated farmbased systems with better process control to generate electricity. With time, AD systems are becoming more complex and not limited to agriculture or animal waste treatment. The technology is now being applied for municipal waste treatment as well as industrial waste. Taiwan flares most biogas from waste treatment and has cut down river pollution, caused by direct discharge from the animal production industry, by simply using standard AD systems that serve 5,000 farms (Lusk, 1996). In recent times, Europe came under pressure to explore AD market because of two significant reasons:

High energy prices and stringent environmental regulations, especially controls on organic matter going to landfills as well as further expansion of landfills (Table 2.1).

Because of environmental pressures, many nations have implemented or are

considering methods to reduce the environmental impacts of waste disposal. Both Germany and Denmark have pledged to double their biogas production by the year 2000 and triple it by the year 2005 (Lusk, 1996). The incentive comes from the "Green-Pricing" initiative of government that allows biogas-generated electricity to be sold at a premium. Also, the co-generated “waste” steam and hot water is used in district heating systems, thereby earning additional revenue for project developers. Some AD facilities in Europe have been in

operation for over 20 years. More than 600 farmbased digesters operate in Europe, where the key factor is their design simplicity. Around 250 of these systems have been installed in Germany alone in the past five

years. In addition to farm digesters, Europe leads in large centralized AD systems. Between 1987-95, there were more than 150 new AD plants constructed in Europe (www.biogasworks.com). In Europe, there are 30 large centralized digesters of which 15 are in Denmark alone and 30 more are under construction. The Danish facilities co-digest manure, clean organic industrial wastes, and source-separated municipal solid waste. The AD technology is also used for treating industrial wastewater. The treatment of

high-organic industrial wastewater is less costly by AD than by aerobic composting. There are now more than 1000 vendor-supplied systems in operation or under construction throughout the world. According to Lusk (1996), European plants comprise 44% of the installed systems, with only 14% of the systems located in North America. A large number of plants are located in Brazil treating vinasse from sugar cane-based for ethanol production. Over 35 industries have been identified using AD. They include chemicals processing, fiber, food, waste meat and milk, and pharmaceuticals. In many cases, AD is used as a pretreatment step to lower sludge disposal costs and odors, thus reducing the costs of final treatment onsite or at a municipal wastewater treatment. Both AD and aerobic composting offer a biological route for the recovery of nutrients from

the organic fraction of MSW. However, aerobic composting is energy consuming, requiring 50-75 kWh of electricity per ton of MSW input. In contrast, AD is an energy producer, with around 75-150 kWh of electricity generated per ton of MSW input (www.biogasworks.com). Using the data of Table 1.1 of the introductory section and applying the usual 31% efficiency of U.S. power plants using fossil fuels, the electricity generated from methane per ton of MSW processed by AD is calculated to be in the range of 48-104 kWh.

2.2 NOTABLE PROGRESS AND IMPROVEMENTS MADE IN THE FIELD OF BIOREACTOR TECHNOLOGY.

Considering the various types of bioreactors in existence today in relation to the earlier forms of bioreactors, it should be noted unequivocally that significant progress has been achieved in bioreactor technology. The earlier forms of bioreactors had considerably high problems due to lack of in-depth knowledge of the parameters which required considerations during their

design and operations. Lack of adequate bioreactor technology was the major cause of poor performance of these earlier forms of biomethanation (Kale, 2003). The re-mixing problem (where the organic solids removed from the sewage mixes up with it again) encountered in the Septic Tank(fig 2.1) was rectified in the development of Imhoff tank (fig 2.2) and it subsequently paved way for better effluent stabilization and consequently a significant decrease in effluent odour. However, there are given number of disadvantages associated with the Imhoff tank such as:

i. excessive sedimentation in inlet channels;
ii. considerably high fouling of surfaces and wears with waste water solid;
iii. floating of sludge and
iv. undesirable intermittent surging of flow.

2.3 The Chinese Fixed Dome and the Indian floating Cover Biogas Digesters

These (shown in Figs. 2.3 & 2.4) are two simple biogas digester designs which have been developed and are mostly used by people living in the developing countries in order to meet their day to day energy demands. The digestion process is the same in both digesters but the gas collection method

is different in each. In the floating cover type, the water sealed cover of the digester rises as gas is produced and acts as a storage chamber, whereas the fixed dome type has a lower gas storage capacity and requires good sealing if gas leakage is to be prevented. Both have been designed for use with animal waste or dung. The waste is fed into the digester via the inlet pipe and undergoes digestion in the digestion chamber. The temperature of the process is quite important and methane-producing bacteria do their work best at temperatures between 30 – 40 C or 50 – 60 C. It takes from 2 to 8 weeks to digest a load of waste, depending on the temperature. The left-over slurry is removed at the outlet for use as a fertilizer.

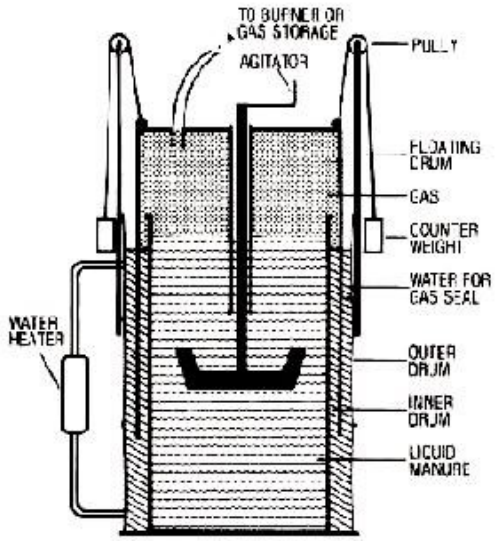


Figure 2.3: Fixed Dome Digester (Image: Practical Action (formerly known as ITDG)

Figure2. 4: Floating Cover Digester (Image: Cooperative Extension Service, Purdue University)
Source: Gitonga (1997).

Tube digester is another form of bio-digester which is designed for use in developing countries. It is tube-like in terms of its configuration and utilizes polythene and for its biogas collection, it employs the use of internal venting pipe; and the mixing and flow pattern is axial. The features of Chinese fixed dome, Indian floating cover and tube digesters are summarized in table 2.2 below; while the comparative analysis of the Chinese fixed dome and Indian floating cover digesters are seen in table 2.3

2.4 THE JANTA BIOGAS DIGESTER (ADI) AND THE FIXED DOME PLUG- FLOW (ADII) ANAEROBIC DIGESTERS

Low rates of biogas production from existing designs of family size (1-6 m^3) biogas digesters is a major constraint to the adoption of biogas technology

in cold hilly areas of India, Kalia (1998). Around 12000 Janta biogas digesters (an Indian version of the Chinese fixed dome digester) have been built in such areas. This design has an advantage over the conventional Indian design of not having a gas holder (which cannot be easily carried over the hilly terrains) and gives almost the same rate of biogas production as do conventional plants when operated on the plains. However, the Janta fixed dome biogas plant requires modifications in order to increase its efficiency under cold climate in hilly regions. The major drawbacks in the design of the Janta biogas digester are as follows:

(i) The inlet and outlet openings of the digester are close to each other resulting in short circuiting of the path of digesting slurry thus reducing the actual hydraulic retention time (HRT) to less than half the theoretical value from which the volume of the digester is calculated.

(ii) The lighter undigested slurry in the top part of the digester which is approximately at the same level as the outlet, partially escapes to the outlet tank further decreasing the actual HRT.

(iii) The dimensions of the inlet and outlet slurry displacement tanks are incorrect resulting in a significant increase in gas pressure as a result of a collection of only a small volume of gas. This results not only in higher losses of gas from the outlet tank, but also in large variations in pressure of

the delivered gas, affecting the efficiency of gas appliances used. The research work Kalia carried out in 1998 was aimed at developing a modified fixed dome biogas digester with improved biogas production and to compare it with the existing Janta design. He reported that to overcome some of the drawbacks of the Janta fixed dome digester (ADI), it is essential that the inlet and outlet slurry displacement tanks should be positioned as far apart as possible so that the actual retention time of the digesting slurry is increased without increasing the overall HRT of the feed or the volume of the digester. On the basis of report, he showed that a horizontal plug flow digester (AD II), fig 2. 5 produces nearly 20% more biogas from manure as compared to conventional mixed flow digester.

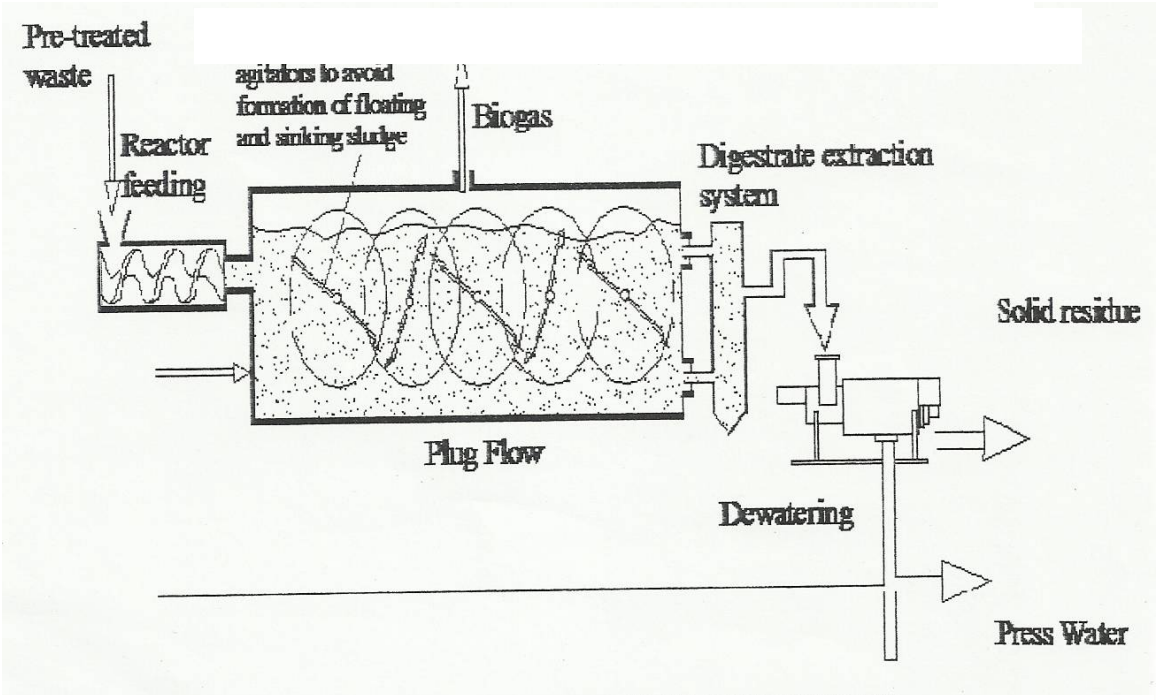


Fig. 2.5: Schematic diagram of the fixed dome Plug flow biogas digester ADII

The outlet opening fixed dome flow anaerobic digester is usually set at 300 mm below the datum (level of initial feeding to digester) compared to 218 mm of ADI, in order to provide an additional gas seal and restrict the movement of undigested slurry from the top of digester to the outlet. The lower labour required for the construction of ADII is due to the nearly straight wall construction as compared to the cylindrical shape of ADI. Thus ADII is easier to construct and cheaper than ADI by around 10%. See table 2.4.

In the attempt to minimize the problems prevalent in the earlier forms of bioreactors in order to improve on their overall performance in the areas of biogas production; waste treatment, etc., many other forms of bioreactors have surfaced over the years. These reactors will be considered below.

2.5 The Continuous Stirred-Tank Reactor (CSTR)

The Continuous Stirred-Tank Reactor fig 2.6, also known as vat- or backmix reactor, is a common ideal reactor type. A CSTR often refers to a model used to estimate the key unit operation variables when using a continuous agitated-tank reactor to reach a specified output. The mathematical model works for all fluids: liquids, gases, and slurries. The

behavior of a CSTR is often approximated or modeled by that of a Continuous Ideally Stirred-Tank Reactor (CISTR). Cibrorowski (2004), reports that agitation in CSTR increases the rate of heat and mass transfer in digester resulting in a generation of biogas with methane content as high as 76.9%.

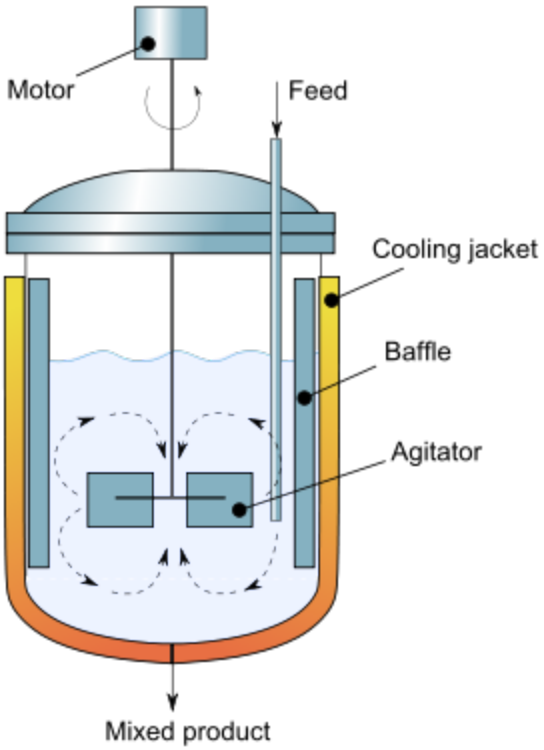


Fig. 2.6: Cross-sectional diagram of continuous stirred- tank reactor (CSTR)

2.6 Upflow Anaerobic Sludge Blanket (UASB) Reactor

This is another type of bioreactor which has a cylindrical configuration. The specific features in the reactor are a sludge bed zone, sludge blanket zone

and a granular zone. It does not require heavy mechanical agitation rather the agitation it experiences is that from produced gas. Unlike fluidized bed reactors there is no need for high rate of effluent recirculation. Its advantage over anaerobic filter and fixed film reactors is seen in the area of the absence of loss of reactor volume through filter material. It does not require a separate settler tank with pump as seen in anaerobic contact digester. The use of (UASB) is a great strategy to achieve high COD removal efficiency in a short period of time (Najafpour et al., 2009). In the case of COD removal efficiency, (UASB) is reported by literature to have up to 78% for the treatment of pulp waste water. The schematic diagram is as shown in fig. 2.7.

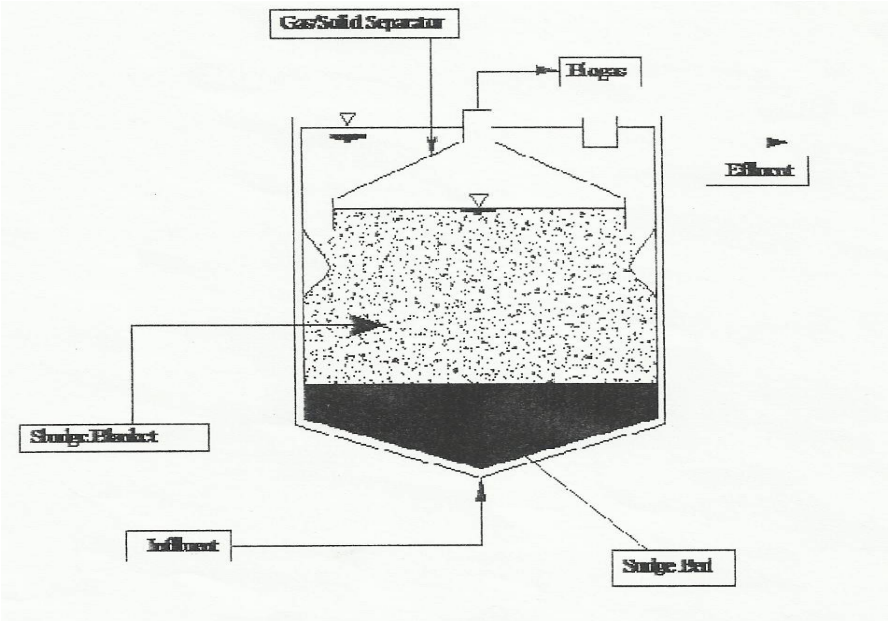


Fig.2.7 Schematic *diagram* of Upflow Anaerobic Sludge Blanket (UASB) Reactor

2.7 The Upflow Anaerobic Filter Process (UAFP) Reactor

This is another type of bioreactor with cylindrical configuration. It possesses a medium which provides microbial support. Microorganisms are grown as biofilm on the medium which may be made of pieces of rocks, plastics, etc. this is shown in fig. 2.8 below:

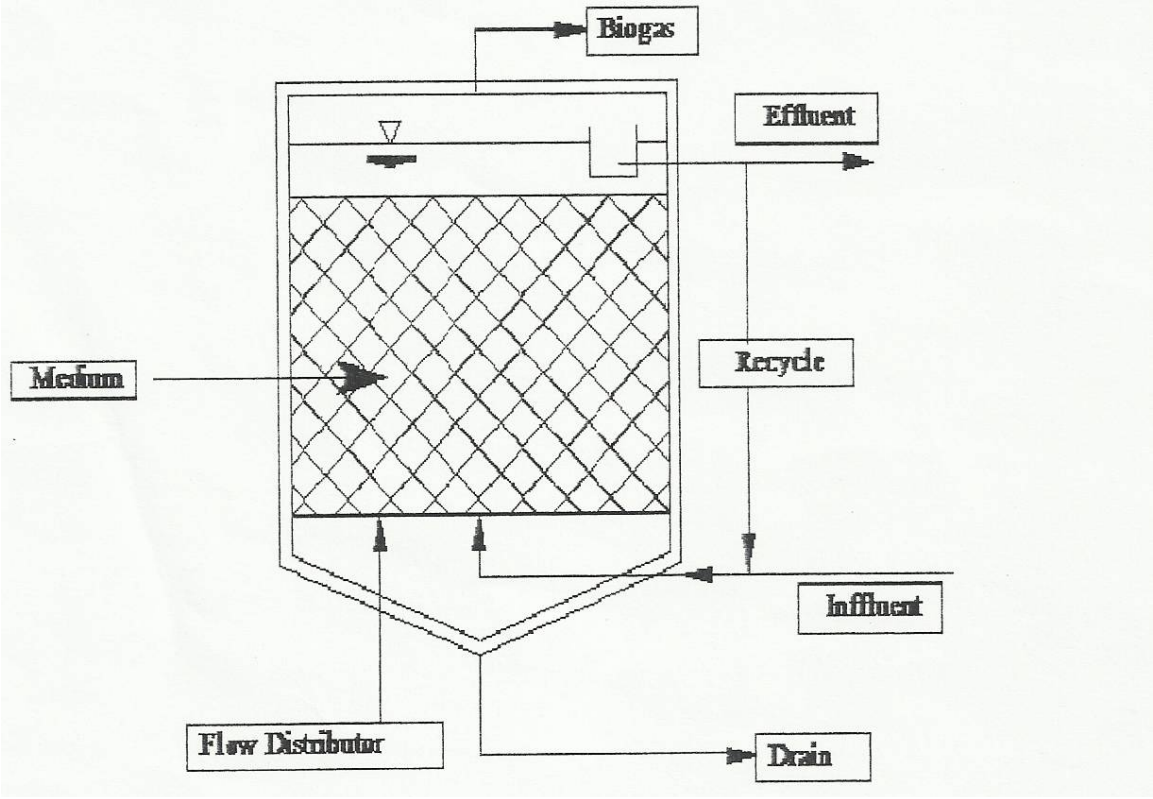


Fig. 2.8: Schematic diagram of Upflow Anaerobic Filter Process (UAFP) Rector

The organic matter is digested as it diffuses into the biofilm on the solid support matrix from base of the reactor. It is suitable for high strength waste water treatment. Literature reports an application of UAFP reactor in which COD removal was between 20-30 % more than in cross flow systems.

2.8 Anaerobic Fluidized-Bed Reactor (AFBR)

This type of bioreactor is also of cylindrical configuration but with particles of medium fluidized within the reactor.

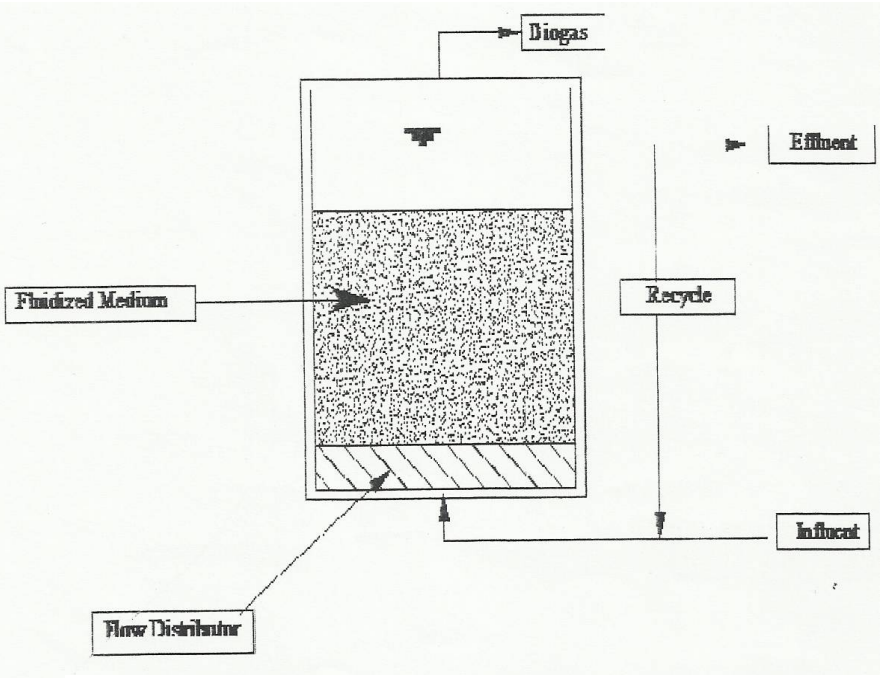


Fig. 2.9: Schematic diagram of Anaerobic Fluidized-Bed Reactor(AFBR)

Microbes get attached to the fluidized medium and grow in suspension. It utilizes media such as sand, alumina, granular activated carbon etc,. The system is tolerant of shock loading of organic substrate and temperature. Unlike Upflow Anaerobic Sludge Blanket (UASB) Reactor, it requires high

rate of effluent recirculation and consequential high pump energy. It is reported by literature to have over 80% COD removal efficiency in the treatment of sewage water at 20^{o}C. Its schematic diagram is as seen in fig. 2.9 above.

2.9 HYBRID BIOREACTOR (FIG. 2.10)

Industries generate wastewater that contains a mixture of different pollutants, which often suffer from low biodegradability and are recalcitrant to biological treatment. Owing to a great variability of chemical structure and properties of compounds present in industrial wastewater and the risk of toxicity, conventional biological processes, even though commonly used due to their low costs, are seldom efficient. However, the urgent need of developing innovative treatment technologies capable of degrading toxic or refractory pollutants present in the wastewater led to the development of Hybrid Bioreactor as shown in (fig.2.10) above. The anaerobic hybrid reactor combining the sludge blanket in the lower part and filter in the upper part has been reported to promote the advantages of both upflow anaerobic sludge blanket (UASB) and upflow filter, while minimizing their limitations (Kimata et al., 1993 and Guiot and van den Berg, 1985). Since its conception, this hybrid reactor has been studied by many researchers and

found to be efficient in treating dilute to medium strength wastewaters (Ramjeawon et al., 1995, Fang and Kwong, 1994, Bardiya et al., 1995 and Ozatijrk et al., 1993).

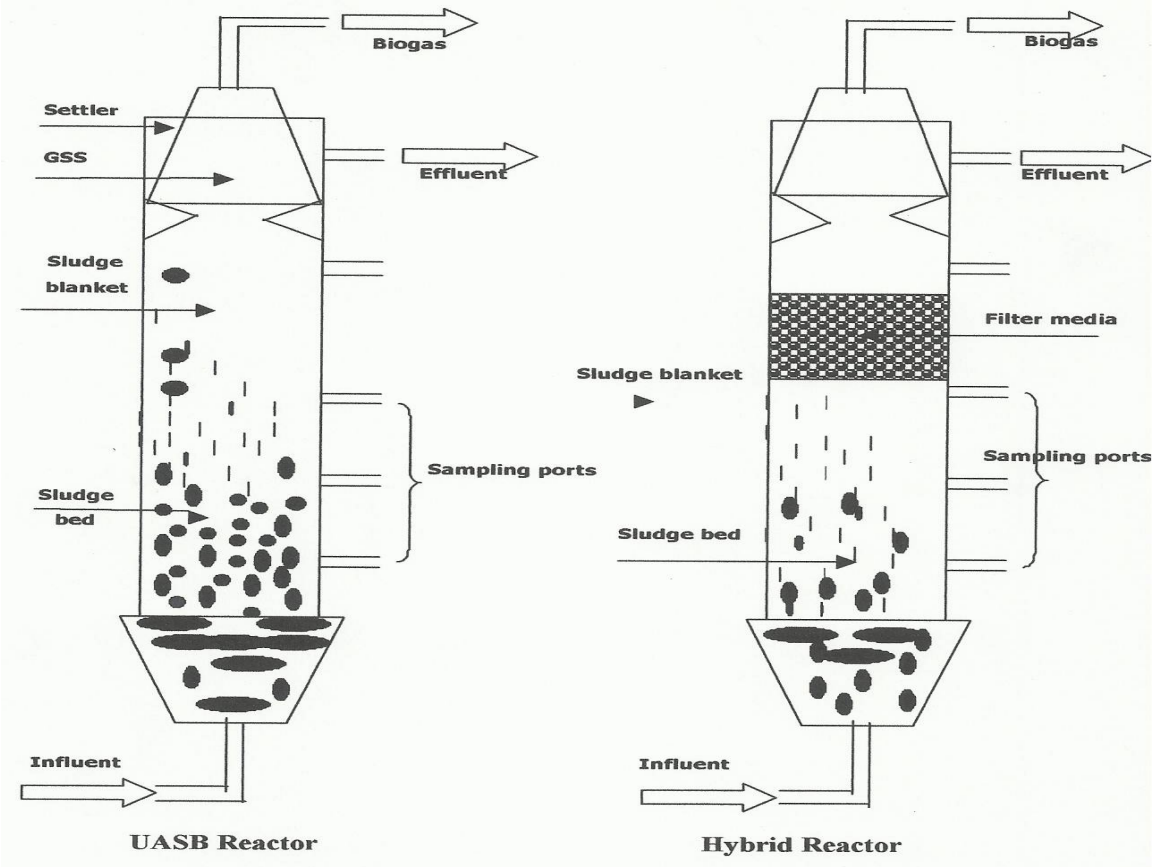


Fig. 2.10: Schematic of UASB and Hybrid Reactor

The researchers (Gupta et al., 2007) reported the following:

- COD removal efficiency and biogas yield of hybrid reactor is found to be 5% more than the UASB reactor.
- The washout of the sludge, a serious drawback of UASB reactor, can be reduced by 25% in hybrid reactor than UASB reactor.
- In terms of shock loading, the hybrid reactor is found to be robust enough to resist the shock load up to 2 times of normal organic load while the UASB reactor could withstand only up to shock loading of 1.5 times.
- Unlike UASB, the Hybrid bioreactor is not susceptible to the problem of plugging and choking of effluent and vent pipes.

2.10 Trends in AD Technology

According to the Bioenergy Report of the International Energy Agency (IEA), in 1996 there were about 90 AD plant around the world and 30 under construction (Table 2.5). This data includes all plants with treatment capacity of over 2500 tons per year. Around 40 companies are involved in marketing AD technology. A 1999 report

by the German Technical Cooperation Agency (GTZ) shows around 400 AD plants worldwide treating both municipal and industrial waste. The Biogasworks (1998) shows a list of 130 plants and 45 process suppliers of capacity varying from 500 to 300,000 tons/year and treating different waste streams. The distribution is presented in the form of a pie chart in Figure 2.11. It can be seen that most of the plants are operating in Europe (91%), with some in Asia (7%) percent and a few in the US (2%). Germany is the leader with 35% of all AD plants, followed by Denmark (16%) and Sweden and Switzerland and Austria (8%).

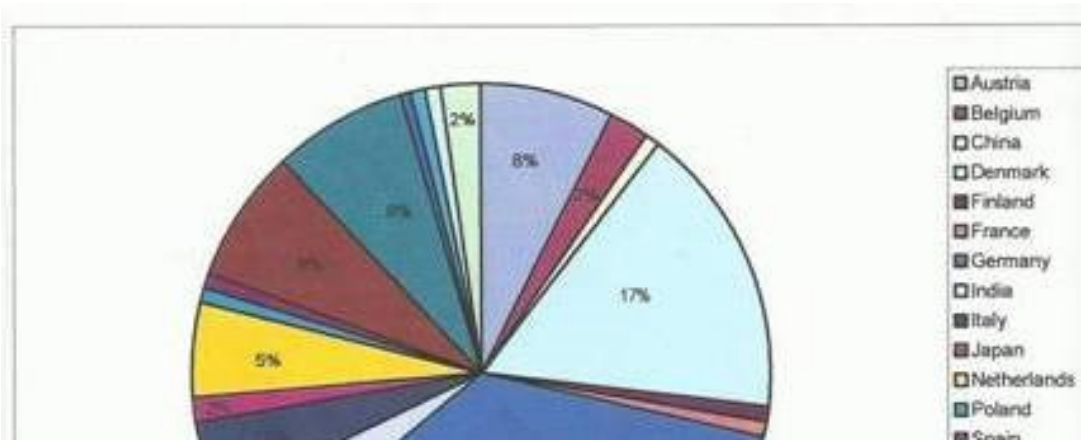


Figure 2.11 Worldwide Distribution of AD plants

(Ref: Adapted from www.biogasworks.com)

The survey of the state of art of AD, with respect to size, capacity and waste-streams and operating parameters, is based on data provided by De Baere (1999). The data included plants operating in Europe

with capacity greater than 3000 tons/year. The trend shows that plant capacity and number of plants built annually increased rapidly since 1996.

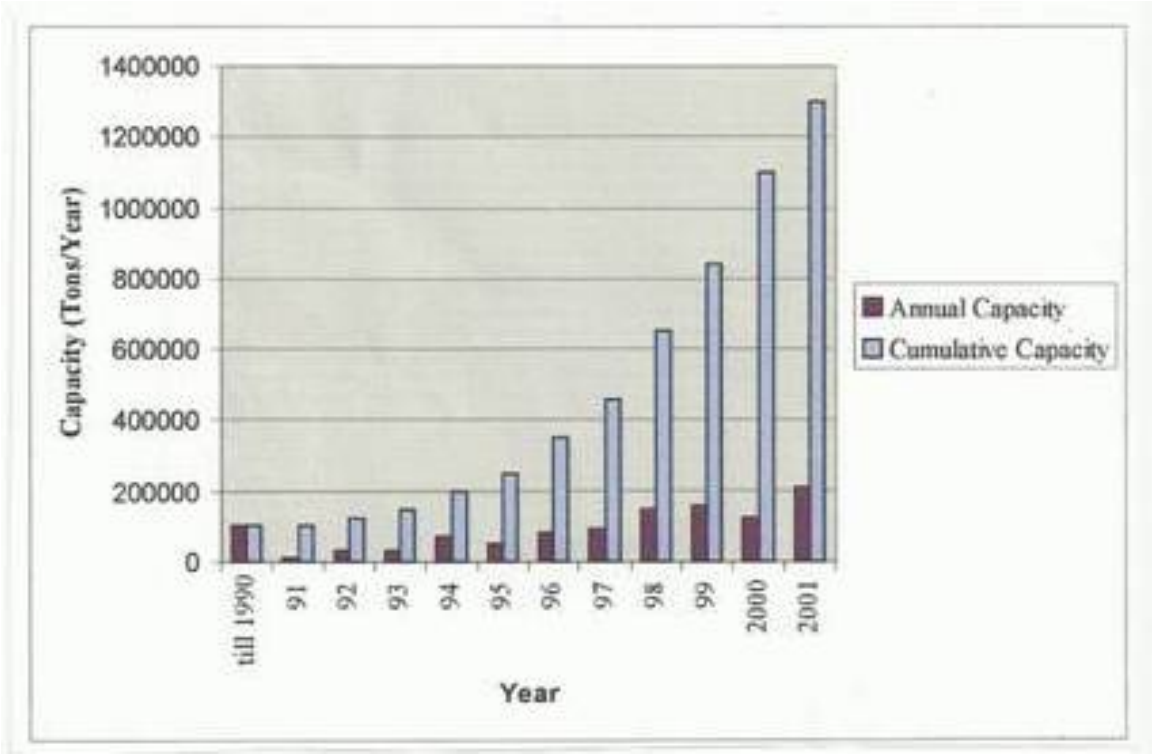


Figure 2.12. Annual and Cumulative Capacity of AD Plants treating MSW

Ref: De Baere, L., (1999) Anaerobic Digestion of Solid Waste: State of the Art, ***Water, Science Technology*** Vol. 41, No 3, pp 283-290

Traditionally, AD plants have operated in the mesophilic range as it was difficult to control the temperature of digester at higher temperature; temperatures above 70° C, can kill the microbes digesting the waste. Along with the advent of high-solids AD, there has been progressing in using the thermophilic range. It is now an established technology and many plants are using it. The benefits offered are hygenizaion of waste, lower retention time and higher biogas yield (National Renewable Energy Laboratory, 1992).

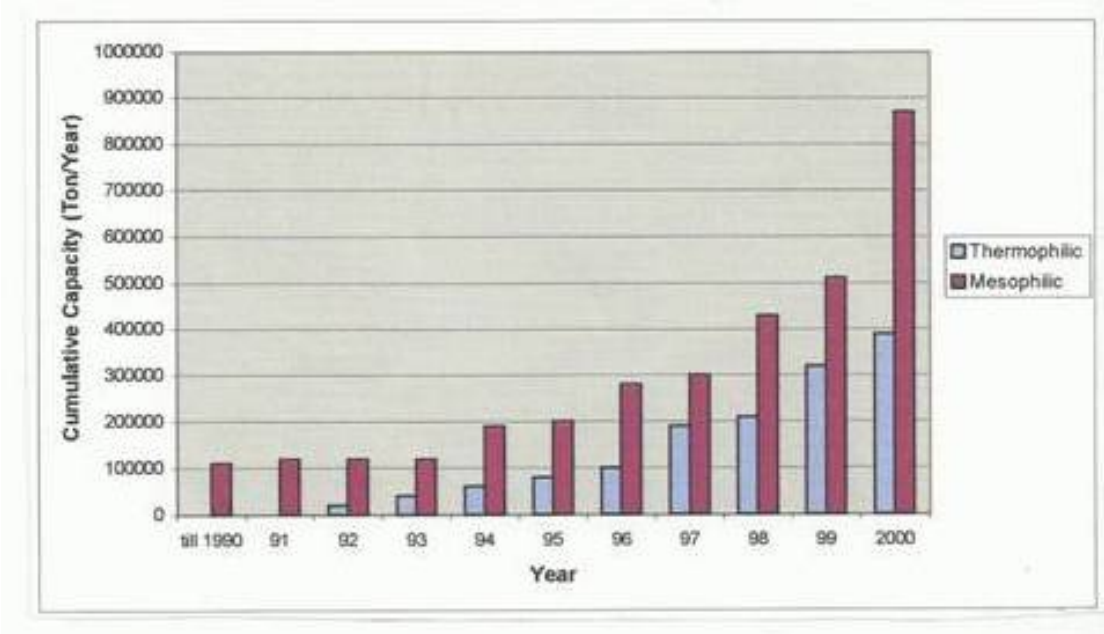


Figure 2.13. Comparison between Mesophilic and Thermophilic AD Plants

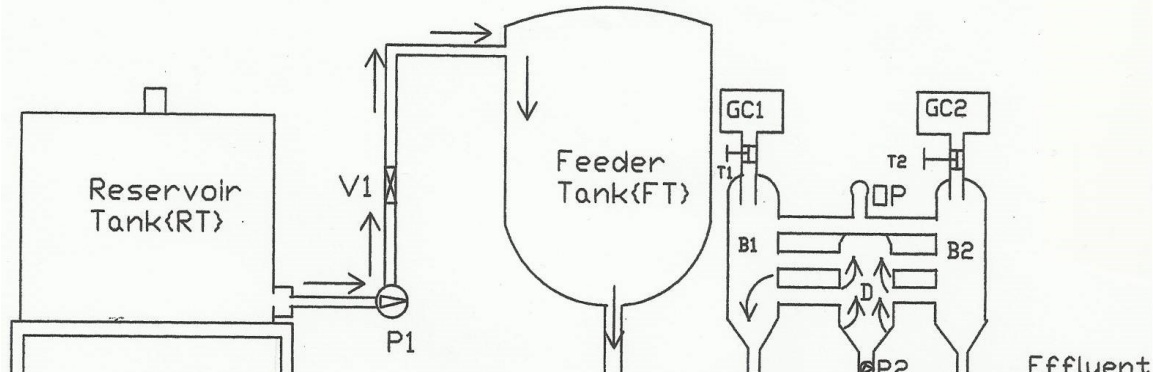
Ref: De Baere, L., (1999) Anaerobic Digestion of Solid Waste: State of the Art, ***Water, Science Technology*** Vol. 41, No 3, pp 283-290

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 UBCSD FEATURES, DESCRIPTION AND PROCESSES

The Upflow Bioreactor with Central Substrate Dispenser UBCSD (figure 3.1), is a recent research development which has been proven to be workable. Basically, the idea is simply its use of inherent features to solve some of the problems associated with the existing bioreactors. As a result of its central substrate dispenser (CSD) feature, it can assist immensely in minimizing the recorded mixing and fouling problems associated with some of the conventional bioreactors. This is expected to assist in enhancing effluent stabilization, biogas production, and consequently pave way for reduction in maintenance requirement problems. The substrate flow processes by which UBCSD is characterized is different from the flow situation observed in standard Upflow reactors and other reactors such as Continuous Stirred Tank Reactors (CSTR), Fluidized Bed Reactors, Sludge Tank Reactor systems etc.,. Its configuration also differs from the others. There are two kinds of flow situations observed in this type of bioreactor viz, a downward flow of substrate effected by gravity, and a cross-flow of substrate achieved by the central dispensing unit (CSD which is discussed in detail in the following pages).



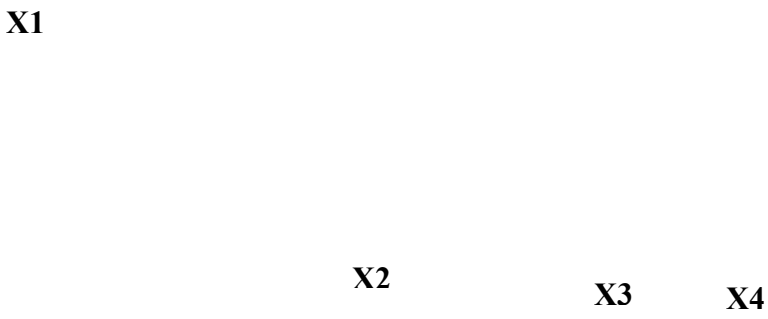


Figure 3.1 schematic diagram of a typical upflow bioreactor with central substrate dispenser considered as a separate reactor. (Source: Agulanna, 2012).

In this research work, the test rig of the bioreactor set-up consists of three different reactors with their component parts assembled systematically to achieve desired results. The major components within the integrated assembly apart from the UASB and CSTR units are as listed below:

- Reservoir tank
- Feeder tank
- Central substrate dispenser
- The twin bioreactors and effluent disposal systems
- Valves, centrifugal and recirculation pumps
- Gas collectors
- Pressure gauges
- Heating elements
- Control panel

3.1.1 RESERVOIR TANK

This tank is stationed on the floor and is basically where the mixture of the organic municipal waste (OMW) and water (i.e. the slurry) is filled. It is connected to the feeder tank by the aid of pipe fittings. A centrifugal pump is used to pump the substrate from the reservoir tank into the feeder tank via an interconnecting pipe. The pump also comes in handy when occasion calls for the cleaning and flushing of the bioreactor vessels and pipe fittings. This time, water is used as the fluid to achieve this goal. This is seen in figure 3.2 below.

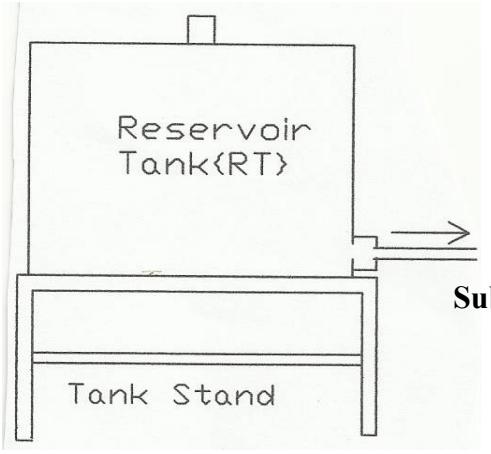


Figure 3.2 Schematic diagram of the Reservoir Tank

3.1.2 THE FEEDER TANK

The feeder tank is designed with steel material and is connected to the reservoir tank from which it receives the substrate by means of pipe fittings.

It is further connected to the bioreactors via interconnecting pipes. Its basic function is to feed the reactors with the substrate. However, whenever the required amount of substrate needed for the fermentation process is fed into the reactor vessels, the substrate supply from the feeder tank is cut off by the use of valves (represented with letter X in the diagrams) fitted to the interconnecting pipes. The tank is positioned at a height considerably higher than the level at which the bioreactors are placed so that the substrate can be inducted into the UASB, the twin bioreactor vessels- UBCSD and the CSTR under the influence of gravity. This was designed to accommodate up to a substrate volume of 250litres.

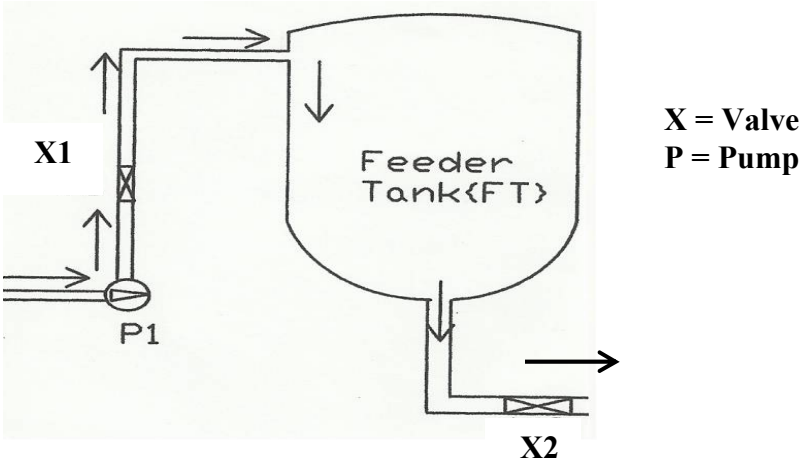


Figure 3.3 Schematic diagram of the Feeder Tank

3.1.3 THE CENTRAL SUBSTRATE DISPENSER (CSD)

The basic function of the dispensing unit (figure 3.4) is to generate an up-flow, down-flow and cross-flow of the substrate within the twin bioreactors to which it is connected it has horizontal pipe fittings as shown in figure 3.5.

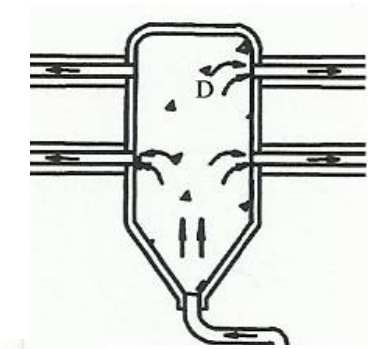


Figure 3.4 Schematic diagram of the central substrate dispenser(CSD)

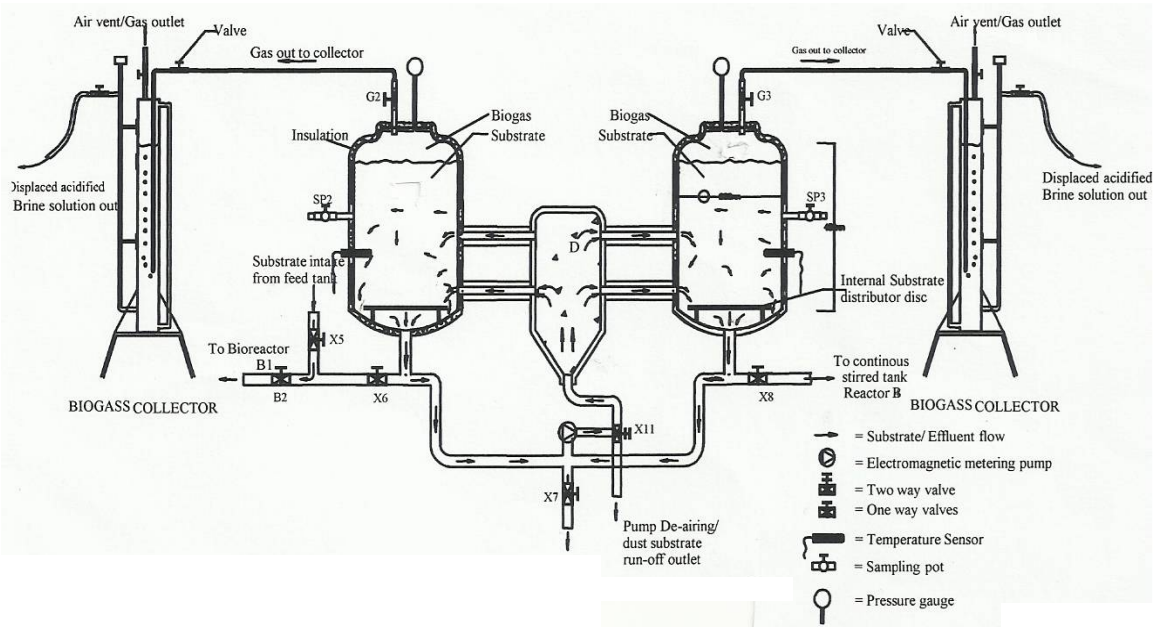


Figure 3.5 Schematic diagram of the twin bioreactor vessels connected with the central substrate dispenser, each attached to its biogas collector.

The dispenser is designed to be of smaller capacity when compared with the size of the twin bioreactors. It has a volume of 8litres while each of the twin reactor vessels has a volume of 28.4litres. During operation, it receives the substrate material and under pump pressure, causes its recirculation within the twin bioreactors so that adequate mixing of the substrate will continuously be achieved. From the 27th Symposium on Biotechnology for fuel and chemical, it was revealed that without mixing, reactor performance deteriorates in a short time, whereas with mixing, continuous production of methane is observed in a longer period of time. So, the incorporation of the central dispensing unit into the bioreactor system is geared towards effecting the recirculation of the substrate within the bioreactor vessels in order to maintain homogeneous substrate front. This will certainly go a long way in preventing the occurrence of sedimentation of the solid particles of the substrate; hence the fouling of the digestion process is prevented.

3.1.4 SUBSTRATE PUMPS AND SPECIFICATION

Two kinds of pumps are required in the course of this bioreactor operation, viz centrifugal and recirculation pumps. It is intended that a centrifugal pump will be used to pump the substrate from the reservoir tank into the feeder tank which in turn helps to induce the slurry into the twin bioreactor

(as seen in figure 3.1 above) under the influence of gravitational force. The pump specification selected for this job is a centrifugal pump (MAR QUIS MKF) of 0.2kw, 5m^3/s discharge. The other type of pump to be used in this work is one which is intended to effect the recirculation of the substrate within the twin up-flow bioreactors via the central substrate dispenser (CSD) unit. Considering a three(3) hours Hydraulic Retention Time (HRT), the pump selected to do this job is of the specification, 0.0024kw, with the maximum discharge of 450ml/min and maximum discharge pressure of 0.2MPa, and model- (EHNC-26).

3.1.5 VALVES

The valves used in this bioreactor system helped to regulate the flow of substrate within the biogas plant by opening, closing, or obstructing various passageways at appropriate times. Valves technically, are pipe fittings, but are usually discussed as a separate category. In an open valve, the slurry flows in a direction from higher pressure to lower pressure. The valves used in this experiment are not automatic, rather they are operated manually at set periods to achieve desired goals. These valves have handles with which they are manually controlled from outside the valve body.

3.1.6 BIOGAS COLLECTOR

The biogas collector was designed and constructed at the workshop complex of Project Development Institute (PRODA), Enugu, under the Department of Engineering Research Development and Production. See figure 3.6. The material used for its construction was stainless steel. Its primary objective is to help remove as much as possible the biogas produced within the biogas plant so that the upcoming biogas generated from subsequent fermentation reactions will be accommodated within the vessel, hence preventing the risk of excessive pressure build up in the bioreactor vessels.

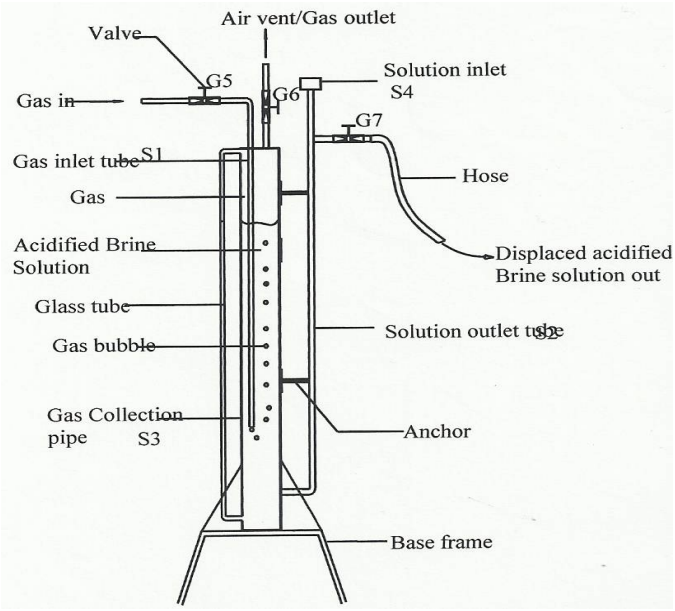


Figure 3.6 Schematic diagram of Biogas Collector

(Source: Agulanna, 2012).

The device uses as its working fluid, a saturated acidified brine solution, coloured with a blue commercial die, for the purpose of helping one to easily identify the liquid levels. It has an external glass tube attachment within which the liquid and gas volumes are observed.

3.1.7 PRESSURE GAUGES

These devices are mounted at the top of the bioreactor vessels. They help to monitor the pressure levels of the biogas produced during the fermentation process in the bioreactors. The amount of biogas generated, if not monitored, may cause a serious hazard as a result of excessive pressure build up within the system. Basically, the reactors are pressure vessels and are prone to undergo explosions if the pressure of the biogas produced is allowed to go beyond the maximum allowable stress prescribed for the vessels. However, to avoid explosive damages, the biogas generated is tapped or collected systematically at certain pressure levels by the use of biogas collectors as shown in figure 3.6

3.1.8 THE CONTROL SYSTEM

The biogas test rig was structured in such a way that provision was made for the incorporation of a control panel. The panel is like a board where

switches, buttons and instruments such as regulators are placed to help operate the bioreactors and control the processes involved efficiently. The function of the instrument panel is to control the operations of the components incorporated into the biogas system such as the feeder and recirculation pumps, the thermostat, the temperature probe, etc,. The thermostat used was of the specification – JTC 903, 0-400 ^{0}C for the control of temperature. It receives an electrical signal input from the temperature probe of specification T-CU/Ni 0-400^{0}C inserted inside the bioreactor. The probe is an alloy which is made of copper(99.95%) and nickel (0.05%) and generates a voltage proportional to the temperature gradient between two ends of a pair of conductors and as a result, an electric signal is produced. Within the circuit, there is a contactor which takes this generated electrical signal as an input quantity and compares it with the value determined by the preset temperature of the thermostat. Therefore, the temperature within the bioreactor is kept fairly constant as the contactor (of the specification-HOA/220v) switches on and off the heating elements when temperatures are below or above the defined level. The thermostat is energized as soon as the start button on the control panel is pressed and this helps to close the open contact. As a result of this, current is allowed to pass through the heating elements to start up the heating process. However, the heating continues

until the temperature of the heating elements reaches the maximum allowable temperature as programmed at the thermostatic unit. The signal goes to the contactor to cut-off the electrical signal by opening the contact already initiated. Besides, the contact is re-established as soon as the temperature is lowered below the minimum allowable temperature so that the heating element could startup the heating process again. This process continues as long as the experiment lasts. Besides, more light will be thrown on the temperature considerations and heating requirements in the pages that follow.

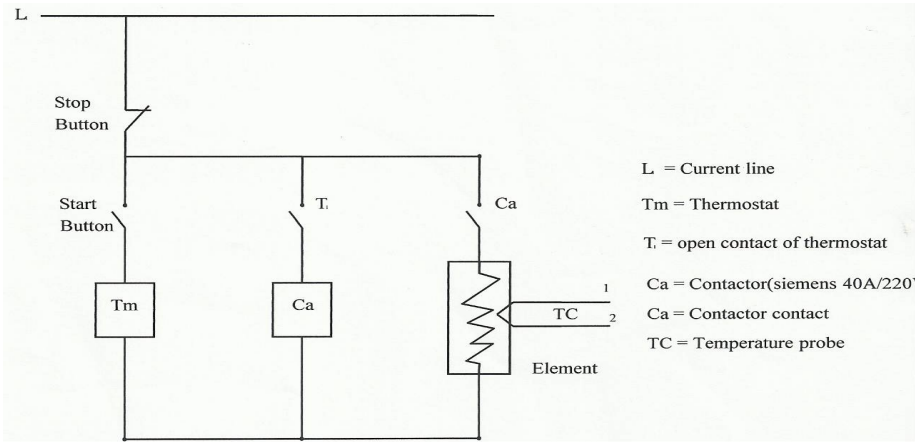


Figure 3.7 Schematic diagram of the Thermostatic Control.

(Source: Agulanna, 2012).

3.2 Parametric Effects of Anaerobic Digestion of Organic Municipal Wastes (OMW) in the reactors

The factors affecting anaerobic digestion in a biogas plant were briefly stated in the introductory part of this work. Here, efforts will be made to present more details of these parameters.

3.2.1 Effects of Substrate Temperature and Monitoring Requirements

Anaerobic fermentation is in principle possible between 3^0C and approximately 70^0C (Habermehl et al., 1999). Differentiation is generally made between three temperature ranges:

- The psychrophilic temperature range which lies below 20^0C,
- The mesophilic temperature range between 20^0C and 40^0C and
- The thermophilic temperature range which is above 40^0C.

3.2.1.1 Minimal Average Temperature

The rate of bacteriological methane production increases with temperature, the biodigestive performance could be inhibited or even reduced as a result. In general, unheated biogas plants perform satisfactorily only where mean annual temperatures are around 20^0C or above or where average daily

temperature is at least 18^0C. Within the range of 20-30^0C mean temperature, gas production increases over-proportionately. If the temperature of the biomass is below 15^0C, gas production will be so slow that the biogas plant is no longer economically feasible, Kossmann et al. (1999)

3.2.1.2 Changes in Temperature

The process of bio-methanation is very sensitive to changes in temperature. The degree of sensitivity, in turn, is dependent on the temperature range. Brief fluctuations not exceeding the following limits may be regarded as still un-inhibitory with respect to the process of fermentation.

- Psychrophilic range: ± 2^0C/h
- Mesophilic range: ± 1^0C/h
- Thermophilic range: ± 0.5^0C/h

According to Wales Centre of Excellence for Anaerobic Digestion, mesophilic bacteria have an optimal temperature for growth between 30^0C and 40^0C but typically around 35^0C. In this research work, the organic decomposing bacteria will be introduced into the bioreactor by employing the mixture of cow rumen with the substrate. These microbes hardly survive when the cow rumen temperature rises considerably beyond the mesophilic range. The microbes die when the temperature rises up to 50^0C (Gong,

2007); hence, efforts will be made to ensure that the temperature is kept within the mesophilic range. It is noteworthy that several different approaches are used in the laboratory fermentators for temperature control. However, considering simplicity and cost, heating element which is recorded to be the cheapest and simplest to handle is used. This is placed between the twin-bioreactor medium as well as other reactors within the test rig to the end of assisting in maintaining the required temperature within the bioreactors. However, in this work, heating coils are used externally to introduce heat energy to raise the temperature of the substrate to about 37^0C by ensuring that the temperature sensor is inserted inside the bioreactor.

3.2.2 Effects of Substrate Content and Properties

The mobility of the methanogens within the substrate is gradually impaired by increasing solids content, and the biogas yield may suffer as a result. Generally, no valid guidelines can be offered with regard to specific biogas production for any particular solids percentage. However, the substrate used for this research work is Organic Municipal Waste (OMW) obtained from Ekeonunwa Market, Owerri, Imo State. MSW is composite in nature and consists of high organic matters. It is the waste generated in a

community with the exception of industrial and agricultural wastes (Tchobanoglous, 1993). Hence MSW includes residential waste (e.g., households), commercial (e.g., from stores, markets, shops, hotels etc), and institutional waste (e.g., schools, hospitals etc). Paper, paperboard, garden and food waste can be classified in a broad category known as organic or biodegradable waste. For instance, the organic compound fraction of MSW in the US represents 70% of the waste composition and consists of paper, garden waste, food waste and other organic waste including plastics. The biodegradable fraction (paper, garden and food waste) accounts for 53% of waste composition (Kayhanian, 1995). The high level of nutrients present in this type of waste provides an enabling environment for some bacterial species to convert organic sources into methane via anaerobic process. The high COD (Chemical Oxygen Demand) level of any organic waste depicts its toxicity

and can be used as an index to state whether it is a pollutant or not. A given number of biological treatment processes are utilized in the treatment of organic wastes (Demirel et al., 2005; Malaspina et al., 1996). Anaerobic treatment process is an ideal technique for bioconversion of organic wastes to biogas. In comparison to aerobic process, the system does not require aeration but generates biogas as energy source (Erguder et al., 2001; Gerardi., 2003). However, the analysis of a sample of the MSW sourced from Owerri Central Market gives the following components by weight of the material as listed in table 3.1.

This municipal waste underwent pretreatment by sorting . The separation ensures removal of undesirable or recyclable materials such as glass, metals, stones etc. In source separation, recyclables are removed from the organic wastes at the source. The removal of the inert fraction of MSW which contains stones, glass, sand, metal, etc prior to digestion is important as otherwise it increases digester volume and wear of equipment. The resultant material after separation (i.e. organic municipal waste [OMW] which is the organic fraction of the MSW)

is then dried in order to make it moisture-free for the sake of preserving it from unwanted decomposition. The dry material was milled to about 500μm size; and finally, during experimental setup, slurry of the waste was made with a measured quantity of water to produce the substrate.

3.2.3 Available Nutrient

In order to grow, bacteria need more than just a supply of organic substances as a source of carbon and energy. They also require certain mineral nutrients. In addition to carbon, oxygen and hydrogen, the generation of bio-mass requires an adequate supply of nitrogen, sulfur, phosphorous, potassium, calcium, magnesium and a number of trace elements such as iron, manganese, molybdenum, zinc, cobalt, selenium, tungsten, nickel etc. "Normal" substrates such as agricultural residues or municipal sewage usually contain adequate amounts of the mentioned elements. Higher concentration of any individual substance usually has an inhibitory effect, so that analyses are recommended on a case-to-case basis to determine which amount of which nutrients, if any, still needs to be added.

3.2.4 Retention Time

The retention time can only be accurately defined in batch-type facilities. For continuous systems, the mean retention time is approximated by dividing the digester volume by the daily influent rate. Depending on the vessel geometry, the means of mixing, etc., the effective retention time may vary widely for the individual substrate constituents. Selection of a suitable retention time thus depends not only on the process temperature, but also on the type of substrate used. Optimizing the process parameters retention time - process temperature - substrate quality -volumetric load determine, among others, the cost efficiency of the biological processes. But as each m^3 digester volume has its price, heating equipment can be costly and high quality substrates may have alternative uses, the cost-benefit optimum in biogas production is almost always below the biological optimum. However, if the retention time is too short, the bacteria in the digester are "washed out" faster than they can reproduce, so that the fermentation practically comes to a standstill.

3.2.5 Organic Loading Rate

Organic loading rate (OLR) is a measure of the biological conversion capacity of the anaerobic digestion system. Feeding the system

above its sustainable OLR results in low biogas yield due to accumulation of inhibiting substances such as fatty acids in the digester slurry (Vandevivere, 1999). In such a case, the feeding rate to the system must be reduced. OLR is a particularly important control parameter in continuous systems. Many plants have reported system failures due to overloading (RISE-AT, 1998).

3.2.6 Effects of pH Level

Anaerobic bacteria, especially the methanogens, are sensitive to the acid

concentration within the digester and their growth can be inhibited by acidic

conditions. The acid concentration in aqueous systems is expressed by the pH value, i.e. the concentration of hydrogen ions. At neutral

conditions, water contains a concentration of 10^{-7} hydrogen ions and has a pH of 7. Acid solutions have a pH less than 7 while alkaline solutions are at a pH higher than 7. It has been determined that an optimum pH value for anaerobic digestion lies between 5.5 and 8.5 (RISE-AT, 1998). During digestion, the two processes of acidification and methanogenesis require different pH levels for optimal process control. The retention time of digestate affects the pH value and in a batch reactor, acetogenesis occurs at a rapid pace. Acetogenesis can lead to accumulation of large amounts of organic acids resulting in pH below 5. Excessive generation of acid produces a toxic effect and consequently inhibits methanogenic bacteria (methanogens), due to their sensitivity to acid conditions. Reduction in pH can be controlled by the addition of *lime or recycled filtrate* obtained during residue

treatment. In fact, the use of recycled filtrate can even eliminate the lime requirement. As digestion reaches the methanogenesis stage, the concentration of ammonia increases and the pH value can increase to above 8. Once methane production is stabilized, the pH level stays between 7.2 and 8.2.

3.27 Nitrogen inhibition and C/N ratio

All substrates contain nitrogen. Microorganisms need both nitrogen and carbon for assimilation into their cell structures. Various experiments have shown that the metabolic activity of methanogenic bacteria can be optimized at a C/N ratio of approximately 8-20, whereby the optimum point varies from case to case, depending on the nature of the substrate. For higher pH values, even a relatively low nitrogen concentration may inhibit the process of fermentation. Noticeable inhibition occurs at a nitrogen concentration of roughly 1700 mg ammonium-nitrogen (NH_4-N) per liter substrate. Nonetheless, given enough time, the methanogens are capable of adapting to NH_4-N concentrations in the range of 5000-7000 mg/l substrate, the main

prerequisite being that the ammonia level (NH_3) does not exceed 200-300 mg NH3-N per liter substrate. The rate of ammonia dissociation in water depends on the process temperature and ph value of the substrate slurry.

3.28 Effects of Substrate agitation

Many substrates and various modes of fermentation require some sort of substrate agitation or mixing in order to maintain process stability within the digester. The purpose of mixing in a digester is to blend the fresh material with digestate containing microbes. Cibrowski (2004), reports that agitation in CSTR increases the rate of heat transfer in a digester, resulting in generation of biogas with methane content as high as 79.6%. Furthermore, mixing prevents scum formation and avoids temperature gradients within the digester. However excessive mixing can disrupt the microbes, so, slow mixing is preferred. To achieve the slow mixing requirement, a recirculation pump is used within the up-flow bioreactors to effect the recirculation of the substrate via

the CSD. The kind of mixing equipment and amount of mixing varies with the type of reactor and the solids content in the digester. According to Kossmann et al. (1999), the most important objectives of agitation are:

- removal of the metabolites produced by the methanogens (gas)
- mixing of fresh substrate and bacterial population (inoculation)
- preclusion of scum formation and sedimentation
- avoidance of pronounced temperature gradients within the digester
- provision of a uniform bacterial population density
- prevention of the formation of dead spaces that would reduce the effective digester volume.

In selecting or designing a suitable means of agitation, the following points should be considered:

- The process involves a symbiotic relationship between various strains of bacteria, i.e. the metabolite from some particular species can serve as nutrient for the next species, etc. Whenever the bacterial community is disrupted, the process of fermentation will remain more or less unproductive until an equivalent new community is formed. Consequently, excessive or too frequent mixing is usually detrimental

to the process. Considering this fact, slow stirring is better than rapid agitation for the achievement of optimum performances.

- A thin layer of scum does not necessarily have an adverse effect on the process. For systems in which the digester is completely filled with substrate, so that any scum always remains sufficiently wet, there is little or no danger that the extraction of gas could be impeded by the scum.

However, for systems such as the one we are dealing with, substrate flow is of substantial importance. Therefore, considering point one (1) above, an electromagnetic recirculation pump with a maximum discharge of 450ml/min ($0.027m^3/h$) and discharge pressure of 0.2MPa respectively was employed in this work. The substrate discharge rate $\boldsymbol{Q}$ at the dispenser due to pump action is $0.027m^3/h$, the effect is halved for each of the twin bioreactor, giving a discharge rate of 0.0135 m^3/h at each of the vessels. The average flow velocity $\boldsymbol{U}$ is given by the expression:

$$\boldsymbol{U = Q/A} \qquad \text{.……3.1}$$

Where $\boldsymbol{A}$ is the cross sectional area of the reactor vessel. Thus, considering the design carried out by Agulanna (2012) for UBCSD on which this research is based, low velocities of 0.27m/h and 6.87m/h were

achieved at the cylinder and frustum sections of B1 and B2, while for the CSD, the velocities of 6.87m/h and 13.75m/h at the cylinder and frustum sections were achieved.

3.2.9 Inhibitory factors

The presence of heavy metals, antibiotics (Bacitracin, Flavomycin, Lasalocid, Monensin, Spiramycin, etc.) and detergents used in livestock husbandry can have an inhibitory effect on the process of bio-methanation. The following table lists the limit concentrations (mg/l) for various inhibitors.

3.31 The Basic Concept and Kinetics of Biochemical Process

The basic components of the biological process are set into motion by making slurry of the dry organic waste. The reason behind the kinetics bothers on the fact that the organic fraction of the waste as carbon source, is brought into contact with water and nutrients, in the presence of biological organisms. Reactions occur which subsequently release carbon dioxide and methane (biogas), which when extracted, represents a large tonnage of converted waste material leaving the reactor. The formation and release or extraction of biogas from the reactor, has a direct relationship to the

reduction in waste mass. This causes a change in the parameters associated with the substrate at the initial stage such as its COD, pH, etc. By examining the component parts of the bioreactors noted above in more detail, it is possible to approximate a basic material balance operating in the bioreactors. From this, an approximate model relating to the reactions which can connect the influent (organic waste + water) to outgoing products (biogas + effluent) is possible. This presupposes the possibility of a situation where one can predict the potential in waste mass as well as the rate of biogas generation. By applying this model to the twin bioreactor vessels with a central substrate dispenser, the factors and constraints of the bioreactor become better defined and appreciated, hence, techniques for modifying the process can be embarked on. Besides, with the knowledge of the foregoing on ground, the designer of these bioreactors for a commercial size, will be enabled to achieve the development of a more practical cost evaluation of the potential benefits of pursuing operations of these biodigesters.

3.32 WASTE DECOMPOSITION AND BIOGAS YIELD

Municipal solid waste has been studied over the years and according to Kuniholm (2002), can generally be said to have an overall composition of the following elements:

- Organic material content 45-50 %
- Inert material content 25-30 %
- Water content 25-30 %

The organic fraction as stated previously, generally consists of food waste, waste paper, garden wastes, diapers/animal waste, textiles, wood, dirt, rubber and plastics. These materials contain a combination of carbon (C) hydrogen (H), oxygen (0), and some nitrogen (N). While these materials are biologically degradable at different rates, it is this fraction that can decompose and with water, under suitable biological conditions form biogas. This decomposition process under anaerobic conditions can be called "methane fermentation", and is a process involving several complex sub-products. The first stage of decomposition involves the formation of organic acids followed by growth of methanogenic bacteria, which produce methane and carbon dioxide. The ultimate products of complete decomposition are primarily methane and carbon dioxide, formed in accordance with the following general theoretical formula as the basic stoichiometry of waste decomposition and methane formation:

Organic waste + water → Carbon dioxide + methane .....….3.2

$C_6H_{10}O_5 + H_2O \rightarrow 3CO_2 + 3CH_4$ (biogas) … …….3.2

or $C + H_2O \rightarrow 1/2CO_2 + 1/2\ CH_4$ (biogas) …….3.4

Considering equation 3.3, a portion of the hydrogen and oxygen necessary for decomposition are contained within the waste materials themselves and a portion is externally supplied (or recirculated) as water and nutrients. Thus sufficient excess external or recirculated water is always necessary to fully complete the reaction. Moreover, water is also essential as the medium for biological growth and movement of bacteria within the waste mass, since each portion of the waste must be subjected to the complex process involved in its breakdown. Accordingly, maximizing waste decomposition and stabilization of the reactor, is by definition a process of optimizing the necessary conditions for the above reaction, which is dependent on providing the mixture of waste and water necessary for maximizing the production and removal of the biogas. Other conditions including pH, temperature, microbial distribution, etc., as previously stated, also play important roles. However, without sufficient water for the reaction and distribution of the organisms, the rate of decomposition, biogas production and waste stabilization will not be optimized. It is also noteworthy that whenever there is insufficient water during the mixing of the waste with

water for the preparation of the substrate of the organic municipal waste, the pumpability of the recirculation pump attached to the central substrate dispenser for the twin reactor vessels will be adversely affected and with time may become completely impaired. Consequently, with this development, sedimentation of the substrate will set in and as a result, the substrate grows stale which leads to fouling of the system. The results that accompany this situation are always unsatisfactory since the bioreactor operation is gradually hampered. However, it is worthy of note that the general technology of anaerobic digestion of complex organic matter is well known and has been applied for over 60 years as part of domestic sewage treatment to stabilize organic wastes. Bal and Dhagat (2001) pointed out that the anaerobic process is more advantageous than the aerobic process in organic waste treatment because of the high degree of waste stabilization, low production of excess biological sludge, low nutrient requirement and production of methane gas as a useful byproduct. Several studies have been carried out for evaluating kinetic parameters and model equations for anaerobic digestion (AD). Prominent among these studies are those carried out by Hu et al. (2002) , Borja et al. (2005) and Jimenez et al. (2004), etc; these are all based on the Monod kinetic model (Monod 1950) and on the revised kinetic model developed by Chen et al. (1980). Several growth rate

kinetic models for the investigation of the performance of reactors are enumerated here. One of the models based on limited substrate consumption is the first-order reaction (Raj and Anjaneyulu, 2005) stated as follows:

$$-dS/dt = k_s S \quad \ldots\ldots\ldots\ldots\ldots\ldots 3.4$$

Where k_s is the rate constant. Equation (3.4) is characterized as exponential growth and substrate concentration profile with respect to HRT as followed.

From equation (3.4),

$$dS/S = -k_s dt$$

or $$lnS = -k_s t + A \quad \ldots\ldots\ldots\ldots\ldots\ldots 3.5$$

Taking the exponent of both sides, we have:

$$S = e^{-kst + A}$$

Or $$S = e^{-kst} \, x \, e^{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots 3.6$$

Let $B = e^{A}$, then,

$$S = Be^{-kst} \quad \ldots\ldots\ldots\ldots\ldots\ldots 3.7$$

Imposing an initial condition, we have at $\mathbf{t = 0, S = S_0}$, then substituting these into equation (3.7), we have:

$S_0 = B\, e^{-ks \times 0}$ *or* $S_0 = B$, then substituting S_0 for B into equation (3.7), we have:

$$S = S_0 e^{-kst} \qquad \text{.....3.8}$$

Where S is the substrate concentration (g/l) and S_0 is the initial substrate concentration.

However, another important kinetic coefficient of anaerobic digestion process is methane yield (Y_M) which represents the performance of a reactor in terms of methane production. The organic removal rate is related to the rate of methane production as stated in equation 3.8 (Zinatizadeh et al., 2006; Metcalf and Eddy, 2003) below:

$$Q_M = Q\, Y_M\, (S_0 - S) \qquad \text{..... 3.9}$$

Where Q is the volumetric feed flow rate (l/day).

The modified Gompertz equation as recommended by Yusuf et al (2011) for the evaluation of biogas yield kinetics from organic wastes is as expressed below:

$$B_t = B_{max} . \exp[-\exp\{(R_b / B_{max}) . e . (1-t)+1\}] \qquad \text{.....3.10}$$

Where B_t is cumulative biogas production with time, B_{max} is the biogas potential, R_b is the rate of production of biogas, 1 is the biogas production lag time, while t is the period of biogas production and $e = \exp(1) = 2.7183$.

Considering the case of Chemical Oxygen Demand (COD) reduction, after an exhaustive study on biodegradation, Ghosh et al (2011), developed a model based on Fenton's reaction in first order kinetics as expressed below:

$$COD(t) = COD(0)e^{-kt} \quad ...3.11$$

Rearranging equation 3.11 we have:

$$COD(t)/COD(0) = e^{-kt} \quad ...3.12$$

Taking the natural logarithm of both sides of equation 3.12, we have:

$$ln\ [COD(t)/COD(0)] = ln\ e^{-kt} \quad ...3.13$$

Or $$ln\ [COD(t)/COD(0)] = -kt \quad ...3.14$$

Rearranging equation 3.14 based on the laws of logarithm, we have:

$$ln\ COD(t) = -kt + ln\ COD(0) \quad ...3.15$$

Where $COD(t)$ is the COD at any time t, $COD(0)$ is the initial COD and k is the constant for first order kinetics.

Equation 3.15, conforms to a straight line graph which is generally given as:

$$y = mx + c \quad …3.16$$

Where the dependent variable $y = ln\ COD(t)$, m corresponds to the negative slope $-k$, the intercept c, is equivalent to the constant, $ln\ COD(0)$ and the independent variable x represents the function- time, t. However, these models as shown in equations 3.10 and 3.15, will be used to

investigate the performance of the reactor by employing the use of MATLAB programme.

3.41 Experimental Set Up

This experiment was conducted within an integrated assembly of three different bioreactors being operated at the same time and subjected to be under the same working conditions for the sole purpose of comparing their

performances. These reactors are: (a) the upflow anaeronic sludge blanket (UASB) reactor (b) the upflow bioreactor with central substrate dispenser (UBCSD) and (c) the continuous stirred tank reactor (CSTR).

Figure 3.8 Fabricated pilot scale of the integrated assembly of three different bioreactors, UASB, UBCSD and CSTR (Agulanna 2012).

These reactors were designed, constructed and assembled at the workshop complex of Project Development Institute (PRODA), Enugu, under the Department of Engineering Research, Development and Production. They share common reservoir and feeder tanks as seen in Figure 3.8, and for the purpose of achieving a good and justifiable assessment on the performance of the reactors, the pilot scale reactors were designed and subjected to

similar operating conditions. The upflow anaerobic sludge blanket (UASB) reactor has an internal volume of 76litres, the upflow bioreactor with central substrate dispenser (UBCSD), 64.8litres and the continuous stirred tank reactor (CSTR), 76litres. And the sum of these volumes was intended not to exceed the volume of the feeder tank which has a volume of 250litres so that the amount of substrate contained in the feeder tank can be sufficient enough to feed the vessels within the three bioreactor units. However, although these biogas plants were subjected to a test within an integrated assembly, our attention will be more focused on the UBCSD which is our major consideration, since it is the actual unit upon which our research is based.

3.42 Experimental Preparation

Several steps were undertaken in order to prepare the bioreactor system for the actual experimental phase. These steps were geared towards eliminating any substances that could pose to be problematic during the running of the actual experiment. The first step was intended to get rid of any unwanted oily or chemical substances from the vessels or interconnecting pipes. Besides, to achieve this objective, the solution of 5litres of mild soap and 245litres of distilled water was fed into the assembled bioreactor system. The feeder tank, the upflow anaerobic sludge blanket (UASB or B1) reactor,

the twin bioreactor vessels UBCSD (or B2&B3), the central dispensing unit as well as the CSTR (or B4) were completely filled with this solution.

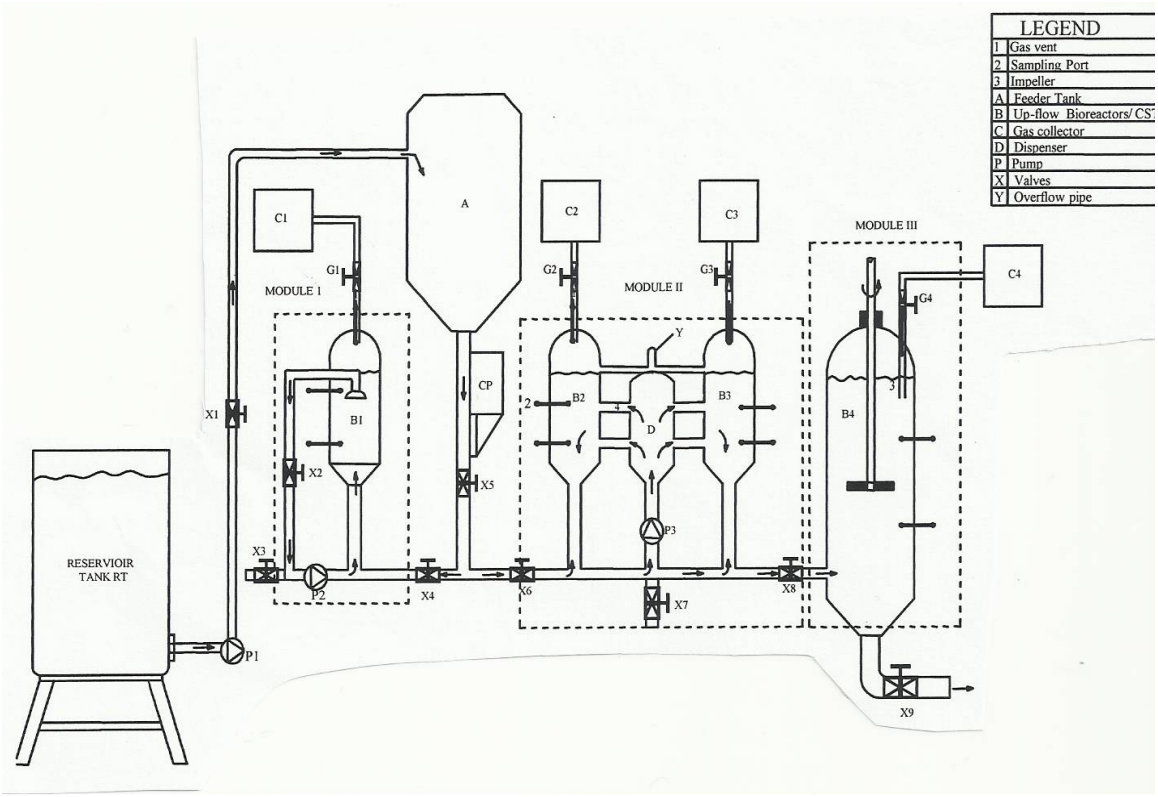


Figure 3.9 Schematic diagram of the test rig of integrated assembly of three different bioreactors UASB, UBCSD and CSTR (Agulanna 2012).

The system was allowed to run for a period of 24hours with the intent to influence practically the dissolution of almost all the resident oily and chemical substances present in the vessels. However, following the expiration of 24hours, the liquid content of the reactor was discharged via the effluent disposal system. Subsequently, the process was repeated, but

this time, the feeder tank and the bioreactor vessels were filled with only distilled water with a view to ensuring that the remaining soapy substances were totally flushed out of the system. To further ensure that the fermentation phase of the actual experiment is not inhibited in the least, the system was finally filled with the actual working substrate and was allowed to run in the system for a period of 4-days to establish an enabling environment for virtually uninterrupted biochemical activities. Following the end of 4-days period, the bioreactor content was as well flushed out just to pave way for the actual envisaged experiment.

3.4.3 The mixing of Organic Municipal Waste (OMW) with water

The Organic Municipal Waste (OMW) was milled into powdered form to produce a 500μm mesh size. A 25kg quantity of this ground OMW was used to prepare the slurry with 250litres of distilled water. The substrate was prepared by the insertion of a mixer into the tank containing the mixture of OMW and distilled water. The mixer was operated for about 30 minutes to achieve homogeneity.

3.4.4 Introduction of the cow rumen content (Inoculation)

Basically, to help enhance the microbial activities during the operation of the bioreactor, a measured quantity (2kg) of some substances from the rumen of the digestive system of a freshly slaughtered cow was mixed with 5litres of distilled water and after undergoing filtration through 100μm sieve, was introduced into the prepared substrate. The rumen is the largest among the four compartments that make up the stomach of a cow. It is practically where fermentation and initial process of digestion occur in the digestive system of a cow. The rumen houses some microorganisms, and its addition into the working substrate was aimed at improving the biodegradation process of the organic content of the slurry by the action of bacteria. The resulting mixture of the slurry and the substance from cattle rumen was then pumped into the feeder tank from the reservoir tank by the aid of the feed pump. However, the filling of the feeder tank was not expected to last more than three(3) minutes so as not to interfere with or affect negatively the actual experimental results, since the biological actions of the microorganisms were expected to have commenced soon after the mixing phase was concluded. The twin bioreactors alongside the other bioreactors then immediately received the mixture (the substrate) from the feeder tank.

3.4.5 Creation of an anaerobic environment

To achieve an anaerobic condition for the fermentation process, the twin bioreactor vessels and the other reactors were completely filled with the substrate to ensure that the void spaces were covered to eliminate all particles of air in the vessel. This de-airing process was achieved with the help of de-airing valves incorporated into the system. Following the de-airing process, it was imperative to create a headspace within the vessels towards their uppermost parts where the gaseous products (biogas) of the fermentation process could be accommodated. This was accomplished by removing one(1)litre volume of the substrate from each of the twin bioreactor vessels leaving a vacuum above the substrate level in each of the twin reactors. As for the UASB and CSTR, one(1) litre volume was also removed from each in order to create a head space in each of them as well. This was achieved with the aid of the valves and electromagnetic metering pumps. The reactors were allowed to run without interruption for a period of 10-days at 37^0C and a recording of the biogas production was made every six(6) hours. The biogas generated was at each set period liberated into the biogas collector tank made of stainless steel pipe of 15cm diameter and 150cm height (see figure 3.6). The gas tank was initially filled with water which was saturated with acidified brine solution, coloured with a blue dye to enhance visibility of the liquid levels. The volume of the biogas was

demonstrated by the displacement of water in the gas collector tank. However, the results obtained during the experimental phase were carefully recorded and tabulated.

CHAPTER FOUR

RESULTS AND ANALYSIS

4.1 Presentation of Results

The results of experiments carried out are presented in Tables 4.1 to 4.7. They show the performance of the three reactors (UASB, UBCSD and CSTR) in terms of biogas production and COD reduction.

4.2 Discussion on the performance of UBCSD relative to other reactors

This work involves evaluating the performance of upflow bioreactors with central substrate dispenser (UBCSD) for the treatment of organic municipal waste (OMW). To investigate the performance of UBCSD, and to compare it with the upflow anaerobic sludge blanket reactor (UASB) and continuous stirred tank reactor(CSTR), a laboratory scale study was conducted with an integrated bioreactor system composed of these three different reactor modules, as seen in figure 3.8 above. The start-up study revealed a limiting factor on organic loading rate (OLR), that is, the particulate nature of the substrate, as higher OLR would consequently lead to the clogging of the metering pumps (Agulanna 2012). To enhance the pumpability of the substrate as well as prevent the clogging of the feeder pump, a strategy was employed which involved the continuous stirring of the substrate within the reservoir tank. This helped pave way for the improvement of the value of the OLR. Subsequently, the homogeneity of the substrate was barely maintained in the upflow bioreactors by the use of the electromagnetic metering pumps, while at the CSTR unit, the agitation of the substrate to prevent sedimentation was achieved by the aid of the impeller powered by an electric motor.

The process parameters such as substrate temperature and flow characteristics were closely monitored. According to Wales Centre of Excellence for Anaerobic Digestion, mesophilic bacteria have an optimal temperature for growth between 30^0C and 40^0C but typically around 35^0C. However, a mesophilic temperature of 37^0C was chosen for this research and the substrate was monitored not to exceed or go below this value. As for the pH, it has been determined as reported by (RISE-AT, 1998) that an optimum pH value for anaerobic digestion lies between 5.5 and 8.5. During digestion, the two processes of acidification and methanogenesis require different pH levels for optimal process control. The chemical oxygen demand (COD) and the biogas yield (Y), which may be regarded as end parameters (because of their usefulness as an index of performance to assess the workability of the UBCSD relative to other reactors) were recorded. The values of the end parameters depend considerably on the process parameters, for which reason, a designer of biogas plants is expected to ensure that during operation, the process parameters are always optimized. Temperature optimization can be achieved by the use of thermostatic control, so that the temperature does not fall below the preset temperature range; while reduction in pH can be controlled by the addition of *lime or recycled filtrate* obtained during residue treatment.

Biogas production lag phase is an important parameter in biodigestion of organic wastes. The research carried out by Budiyono et al., (2010) reported a lag phase of 7-14 days. However, in this work, a lag phase of 12 hours was achieved due to the novel use of rumen of newly slaughtered cattle as inoculants. This method has proven to be highly effective as a result of the fact that the rumen of a cow houses very active microorganisms and is practically where fermentation and initial process of digestion occur in the digestive system of a cow. These microbes played an important role in the biodegradation of the working substrate during the fermentation process.

Comparing the flow of substrate in the two upflow reactors, module I (UASB) and module II (UBCSD), what was remarkably evident was observed, that is, a difference in substrate homogeneity. Considering the UBCSD unit, the nature of the substrate during the operation proved to be a success, in that the combined operations of the metering pump and the central substrate dispenser (CSD) resulted in what could be regarded as a breakthrough in terms of flow situation in bioreactors. The combined operations of the CSD and the metering pump produced and maintained a fairly homogeneous substrate front. This was observed by viewing through the transparent hoses connecting the CSD and the metering pump. The recirculation speed of the metering pump was so controlled that it was not in any way harmful and unfriendly to the biochemical activities; rather, it helped immensely to check stalling of the substrate, and consequently fouling of the digestion process was prevented. Thus, the highest level of COD removal as well as biogas yield was achieved with the UBCSD than with the UASB and CSTR, respectively. But in the case of the flow in the UASB, a partial separation of the substrate particles was observed via transparent hoses connecting the upper part of the UASB vessel and the

bottom part. From the nature of flow encountered in this UASB unit, it could be inferred that the substrate front was not homogeneous and that partial sedimentation occurred since what was continuously recycled was observed to be a substrate front of high watery solution exhibiting a scanty amount of the actual substrate particles. So, it can be posited that the success achieved in terms of the flow situation in the UBCSD was perhaps as a result of the cross-flow characteristics obtained by the use of CSD.

These three reactors were operated continuously for a period of ten (10) days under an anaerobic condition and a mesophilic temperature of 37^0C. As stated in the previous chapter (section 3.4.5), the biogas produced in each reactor was recorded in every six (6) hours as seen in tables 4.1 to 4.3, while the COD values were recorded daily for the period of 10 days as seen in tables 4.4 to 4.6 using EXCEL worksheet.

The percentage COD removed (%tage COD) as presented in tables 4.4 to 4.6, is given by the relation:

$$\%tage\ COD = (COD_{(0)} - COD_{(t)}) / COD_{(0)}. \qquad \text{....4.1}$$

Where $COD_{(0)}$ is the initial COD or the COD at t = 0, its numerical value is = 120320 mg/l; while $COD_{(t)}$ = the COD at any time t.

Considering tables 4.4 to 4.6, it is evident that module II, the UBCSD (or B2 and B3) has the highest level of percentage COD removal of 95.2%, followed by module III, the CSTR (B4) with the value of 80.8%; while module I, the UASB (or B1), offered the lowest level of percentage COD removal of 79.0%.

In terms of biogas production, it could be seen from tables 4.1 to 4.3 that the biogas production for the UASB varied from 9860 mg/l to 1350 g/l; for the UBCSD, it varied from 10200 mg/l to 3950 mg/l; while for CSTR, it was found to vary from 10700 mg/l to 550 ml/day at HRTs from 2 to 7 days respectively. Also, a careful observation of these tables (4.1, 4.2 and 4.3), reveals that towards the end of the experimental phase, the level of biogas produced in each of the reactors reduced significantly, especially in UB and CSTR at HRTs between 168 and 222 hours. The results show that at the HRT of 186 hours, the UB and CSTR had stopped producing biogas, while the UBCSD produced a total of 400 ml of biogas. However, at the end of the 10 days Hydraulic Retention Time (HRT), UBCSD generated the highest level of biogas production cumulatively with the value of 52915 ml, while the values in the UASB and the CSTR were 23550 ml 28980 ml, respectively as seen in table 4.7.

4.3.1 ANALYSIS OF EXPERIMENTAL RESULTS WITH MATLAB PROGRAM

The experimental results obtained for the three reactors were analyzed by the use of MATLAB programme at various HRTs. The process performance of the reactors in terms of COD removal and biogas generation profiles at various HTRs are represented in figures 4.1 to 4.19. This paved way for a comparative study to be made on the UBCSD relative to the other reactors and the resultant information derived to this effect are placed in tables 4.8 and 4.9.

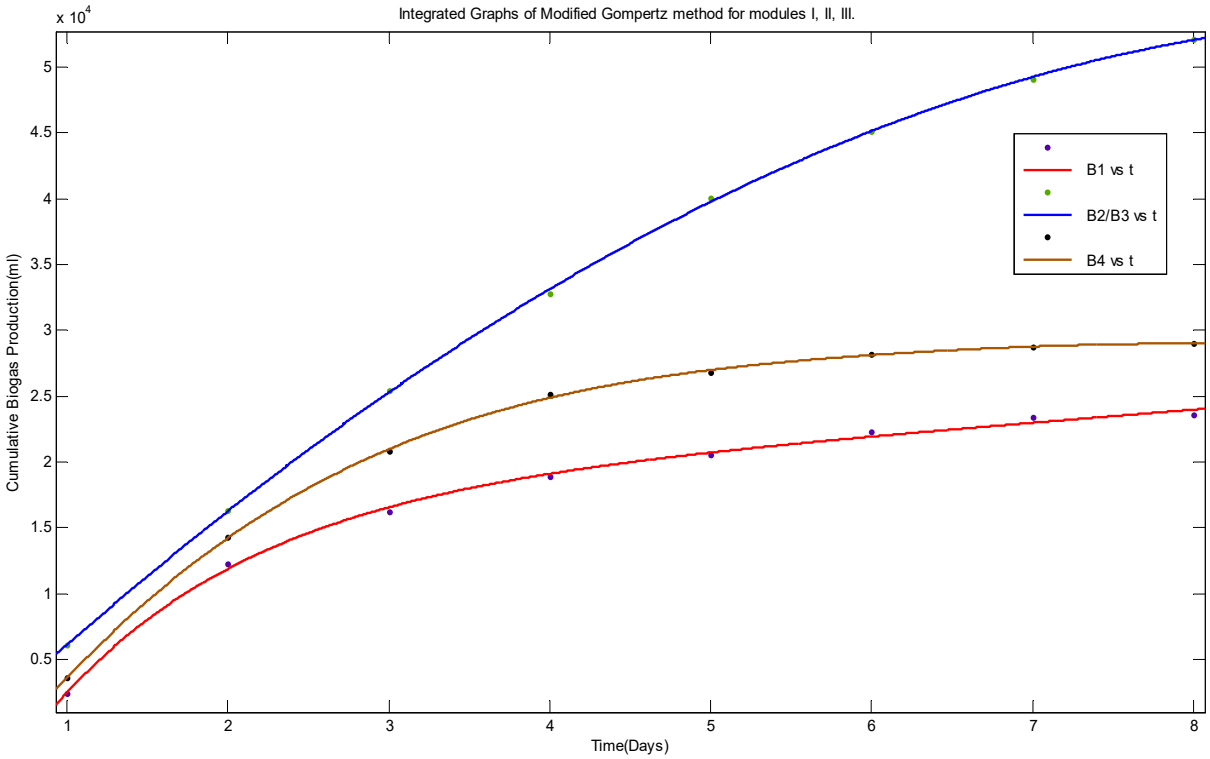


Figure 4.1 Combined plot of cumulative biogas produced vs HRT (days)

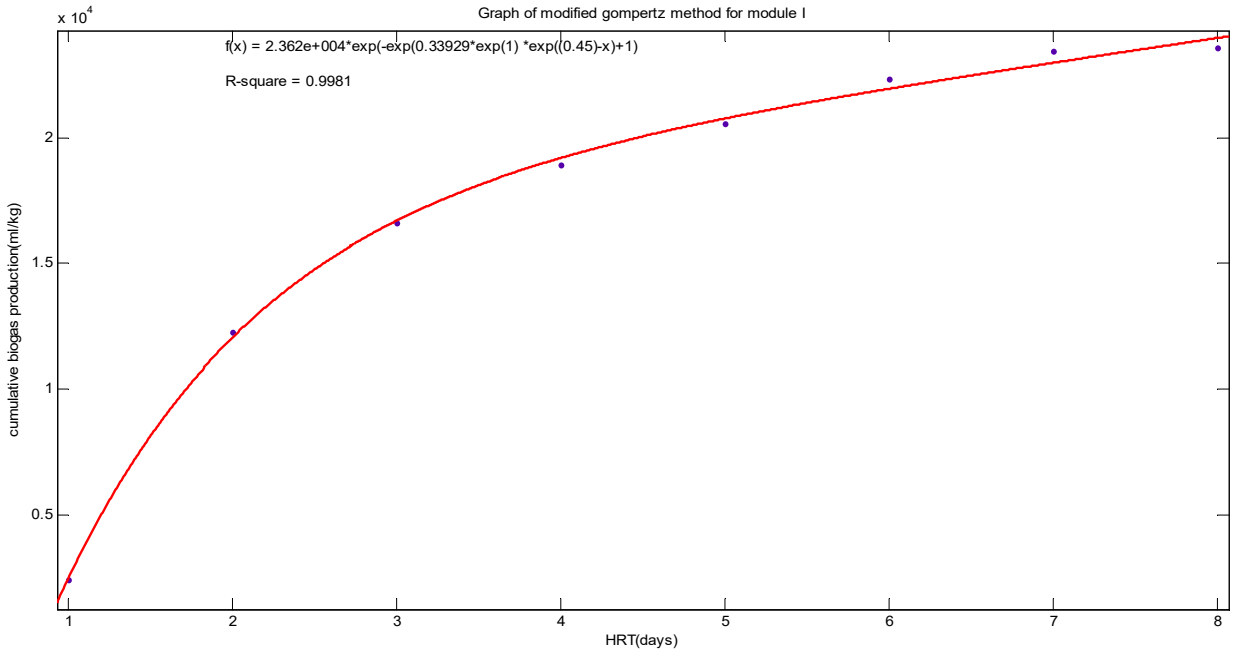


Figure 4.2 Plot of cumulative biogas production vs HRT (days) for module I

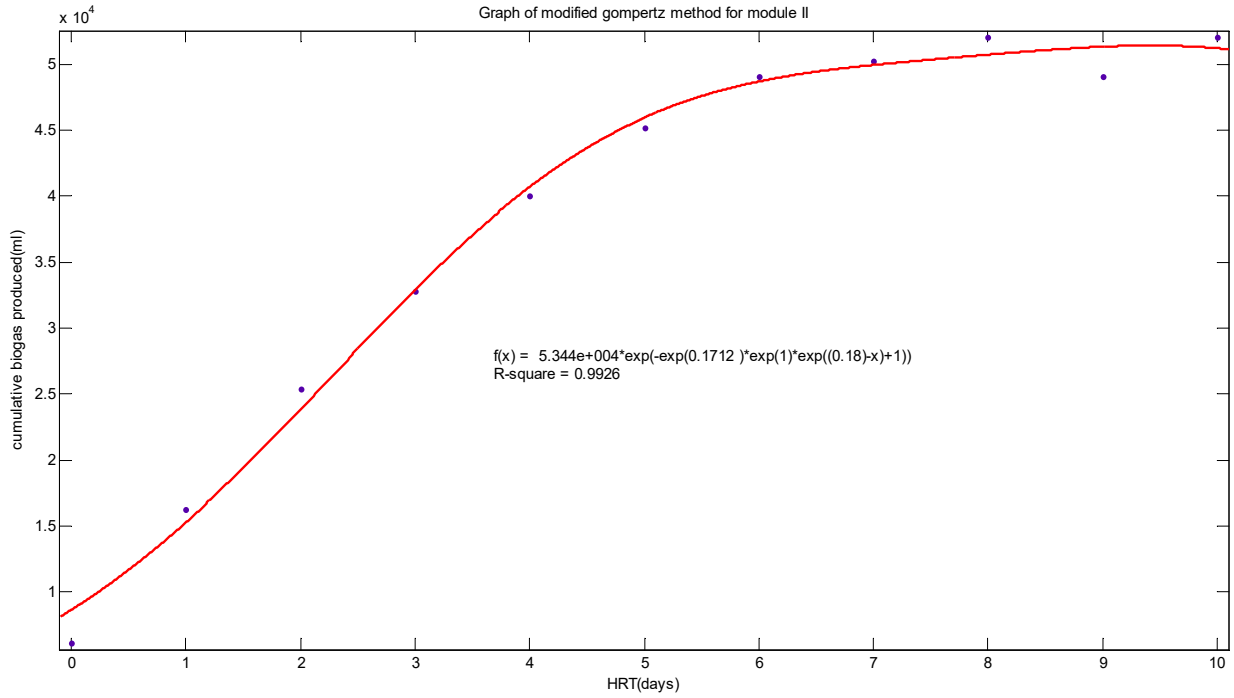


Figure 4.3 Plot of cumulative biogas production vs HRT (days) for module II

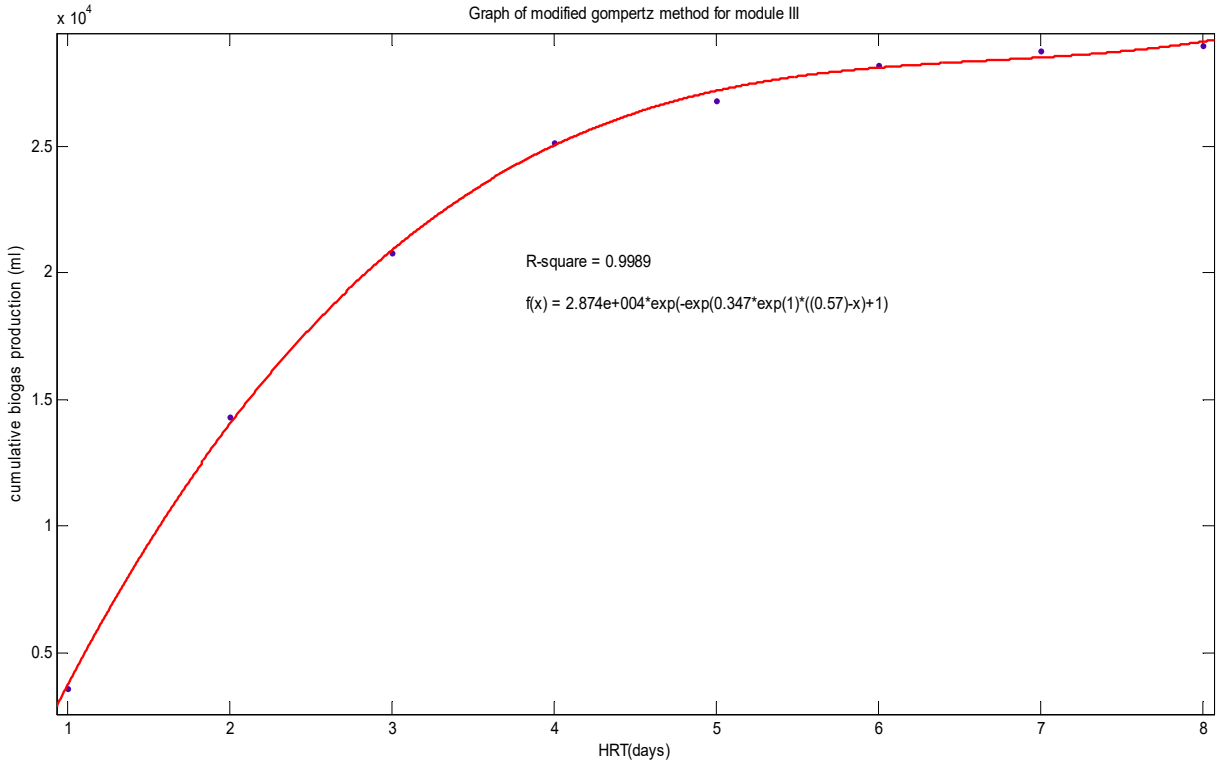


Figure 4.4 Plot of cumulative biogas production vs HRT (days) for module III

In consideration of figure 4.1 in terms of efficiency, biogas production efficiency of UBCSD reactor was found to be the highest compared to the results achieved in the UASB and the CSTR respectively, as demonstrated by the combined plot of cumulative biogas production versus HRT(days).

Besides, from figures 4.2 to 4.4, it can be deduced that the biogas production increased rapidly at HRTs between 2 and 6 days, after which it gradually declined and finally remained constant towards the end of the experiment; at which time, the reactors were observed to have stopped producing biogas. The plots in the above figures correspond to a goodness of fit (R-square values) of 0.9981, 0.9926 and 0.9989, for modules I, II and III, respectively.

Also, by a careful examination of figures 4.2 to 4.4 obtained from a linear regression approach of MATLAB software programme, we can see that the equations generated therein are analogous to and can closely be compared with the modified Gompertz model stated in equation 3.9 in the previous chapter of this work. Thus, this would establish an enabling platform for a convenient evaluation of the kinetic parameters in each of the bioreator modules to be made. However, the results achieved for these kinetic parameters, B, R_b and 1 are tabulated in table 4.5.

4.3.2 DETERMINATION OF THE KINETIC PARAMETERS FOR MODULE I (B1 or UASB)

From the previous chapter, the modified Gompertz model (equation 3.9) was given to be:

$$B_t = B_{max} . \exp[-\exp\{(R_b/B_{max}) . e . (1-t)+1\}] \quad \text{....4.2}$$

Where $e = \exp(1) = 2.7183$. **....4.3**

Considering the cumulative biogas plot versus HRT (days) for module I, figure 4.2,

$$f(x) = 2.362e+004*\exp[-\exp\{0.33929*\exp(1)*(0.45 - x) + 1\}], \quad \text{....4.4}$$

Where $f(x) = B_t$, $e+004 = 10^4$, and $x = t$, respectively. **....4.5**

Therefore,

$$B_t = 23620*exp[-exp\{0.33929*exp(1)*(0.45 - t) + 1\}] \quad \text{…….4.6}$$

Thus, comparing equations 4.2 and 4.6, we have that:

$\mathbf{B_{max}}$ **=** ***23620*** **ml,**

$\mathbf{R_b / B_{max}}$ **= 0.33929**

Or $\mathbf{R_b}$ **= 8014.03 ml/day.**

For the biogas production lag time λ, we have:

λ **= 0.45 days**

4.3.3. DETERMINATION OF THE KINETIC PARAMETERS FOR MODULE II (B2 and B3 or UBCSD)

From figure 4.3, we have the following:

$$f(x) = 5.344e+004*exp[-exp\{0.1712*exp(1)*(0.18 - x) + 1\}], \quad \text{….4.7}$$

Or $B_t = 53440*exp[-exp\{0.1712*exp(1)*(0.18 - t) + 1\}]$ **….4.8**

Comparing equations 4.2 and 4.8, we have the following results:

$\mathbf{B_{max}}$ **=** ***53440*** **ml,**

$\mathbf{R_b / B_{max}}$ **=** ***0.1712***

Or $\mathbf{R_b}$ **= 9148.93 ml/day**

For biogas production lag time, we have that:

λ ***= 0.18 days.***

4.3.4 DETERMINATION OF THE KINETIC PARAMETERS FOR MODULE III (B4)

Following, the foregoing approach, we have:

$$B_t = 28740*exp[-exp\{0.347*exp(1)*(0.57 - t) + 1\}] \quad \text{…….4.9}$$

Hence,

$\mathbf{B_{max} = 28740\ ml,}$

$\mathbf{R_b / B_{max} = 0.347}$

Or $\mathbf{R_b = 9972.9\ ml/day\ and}$

$\mathbf{\lambda = 0.57\ days.}$

The model equations 4.6, 4.8 and 4.9 sufficiently describe the biogas production for modules I, II and III. The values of the kinetic parameters generated by the MATLAB plot of cumulative biogas production with respect to the HRT (days) and the goodness of fit (R-square) values for each reactor are tabulated in table 4.8. However, considering the results achieved from these model equations generated by MATLAB plot in relation to the experimental biogas production, we can see that the numerical values for the kinetic parameters can accurately be approximated to the experimental data tabulated in tables 4.1, 4.2 and 4.3. For instance, the values of the biogas production potential (***B)*** which were obtained (in equations 4.6, 4.8 and 4.9) to be 23620 ml, 53440 ml and 28740 ml, for modules I, II and III can be reasonably compared with the experimental cumulative maximum biogas production tabulated in table 4.7 as 23550ml, 52915ml and 28980ml, respectively.

From section 3.4.5 of the previous chapter, it was stated that one (1) litre volume each of substrate was removed from each of the reactors B1, B2, B3 and B4 for the creation of headspace during the experimental preparatory phase; rendering the working volume of the reactor UBCSD to be 62.8 liters, and those of UASB and CSTR to be 75 liters each, respectively. Besides, realizing the fact that the UBCSD unit exhibits the smallest overall volume, and comparing the level of biogas generation in each of the reactors at the

end of the experiment, it can conveniently be said that the biogas production achieved in the UBCSD is up to 50% more than that achieved in the CSTR and definitely more that 50% than that achieved in the up-flow bioreactor (UASB). The success accomplished in the UBCSD, is believed to be as a result of the central substrate dispenser (CSD) unit incorporated into the UBCSD which helped to generate a cross-flow pattern of the substrate for efficient mixing and maintenance of process stability.

Agitation improves substrate homogeneity and helps in the avoidance of temperature gradient, as it causes an even distribution of temperature. It also helps to blend fresh material with digestate containing microbes. Cibrowski (2004), reports that agitation increases the rate of heat transfer in a digester, resulting in the generation of biogas with methane content as high as 79.6%. So, what is achieved in the UBCSD can be likened to a sort of breakthrough in biogas technology in that it has helped to solve some of the flow problems usually experienced in the conventional bioreactors.

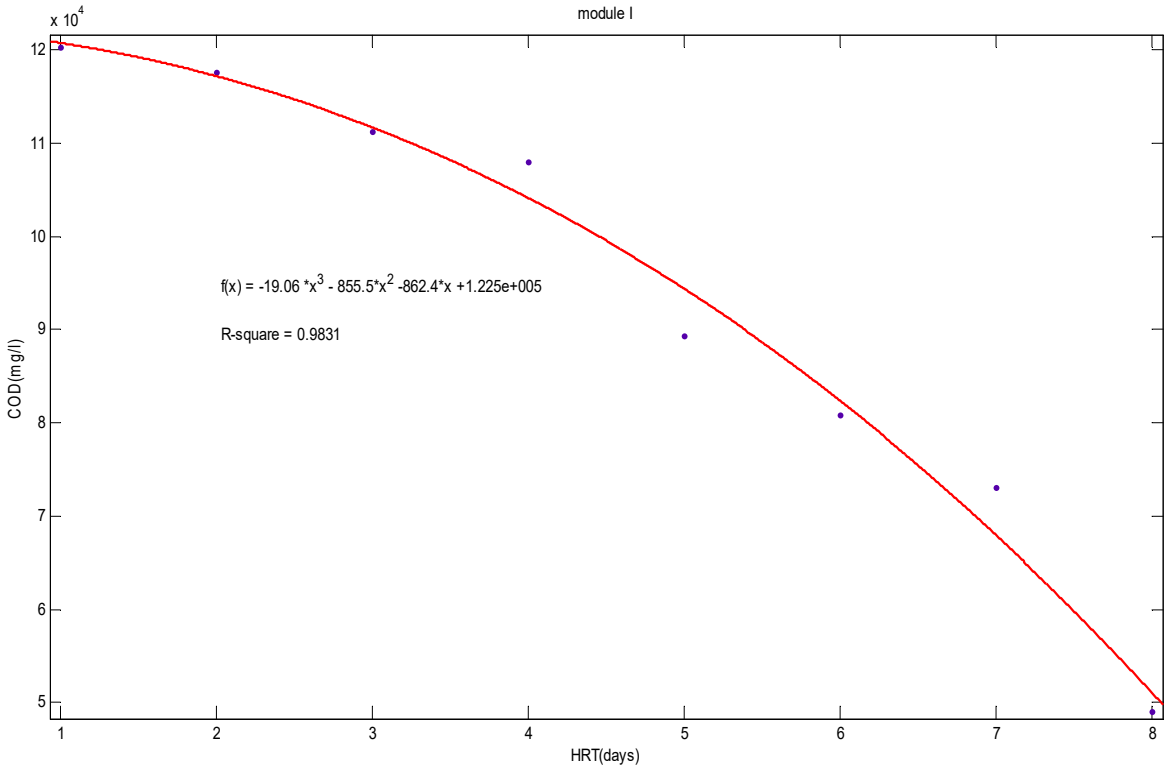


Figure 4.5 Plot of COD versus HRT (days) for module I

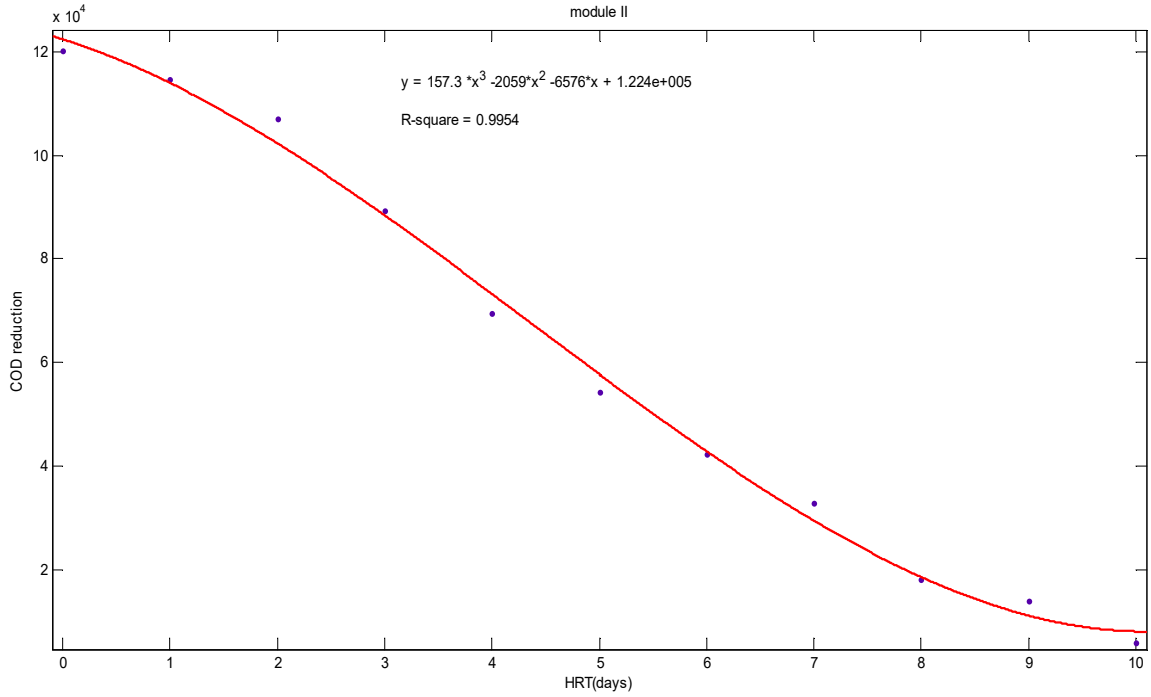


Figure 4.6 Plot of COD versus HRT (days) for module II

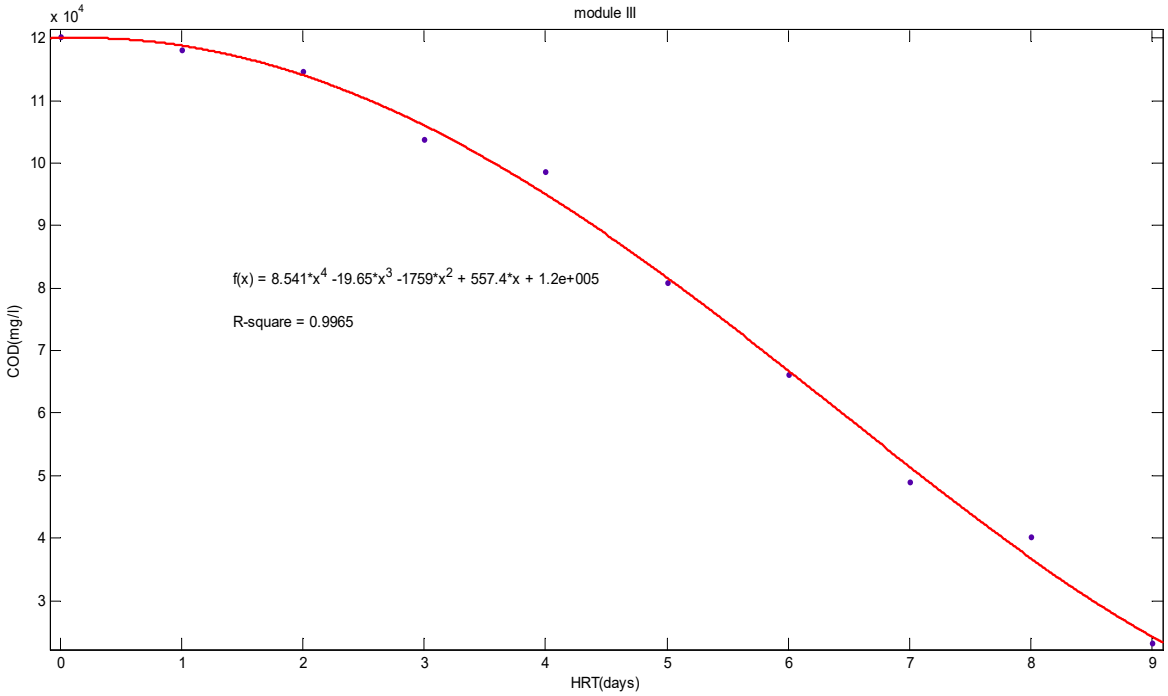


Figure 4.7 Plot of COD versus HRT (days) for module III

4.3.5. COD REDUCTION IN MODULES I, II AND III

Chemical Oxygen Demand (COD) is a measurement commonly used to determine substrate quality. Organic material content enjoys the greatest percentage in the overall composition of municipal solid wastes. According to Kuniholm (2002), the organic fraction is 45 t0 50%. As these substances oxidize or stabilize, they combine with some of the oxygen dissolved in the water. The amount of oxygen used is therefore a good indicator of the amount of waste present. The COD values indicate the amount of oxygen (in milligrams per litre of product) needed to oxidize or stabilize these wastes.

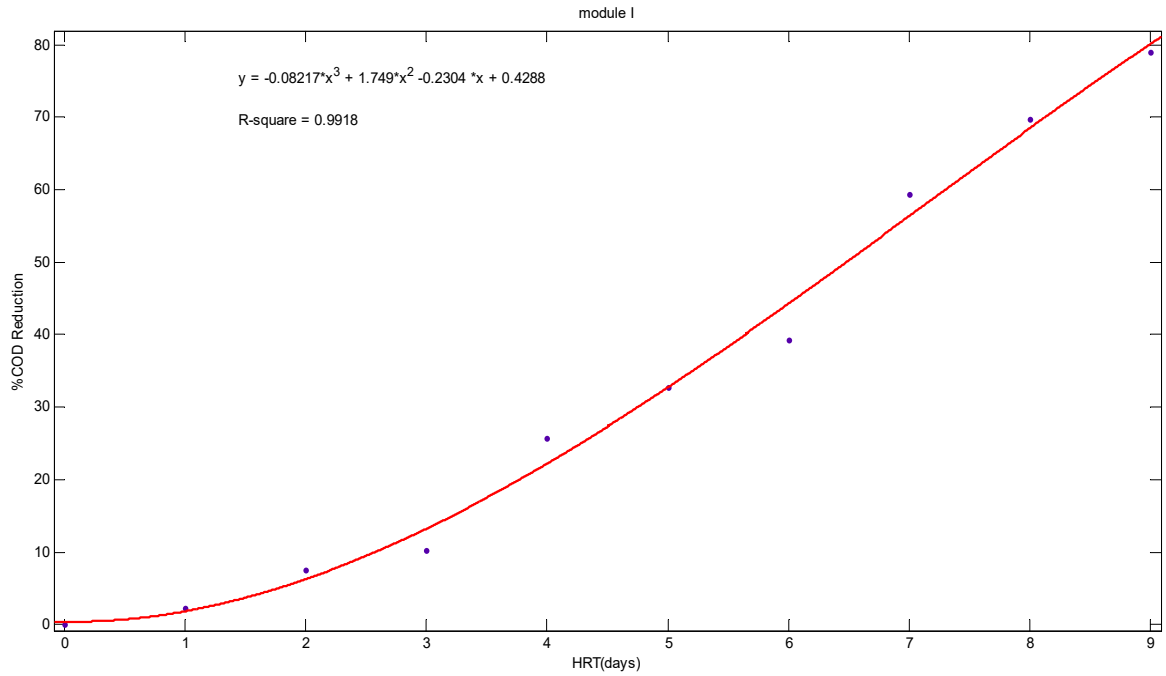


Figure 4.8 Plot of %COD reduction versus HRT (days) for module I

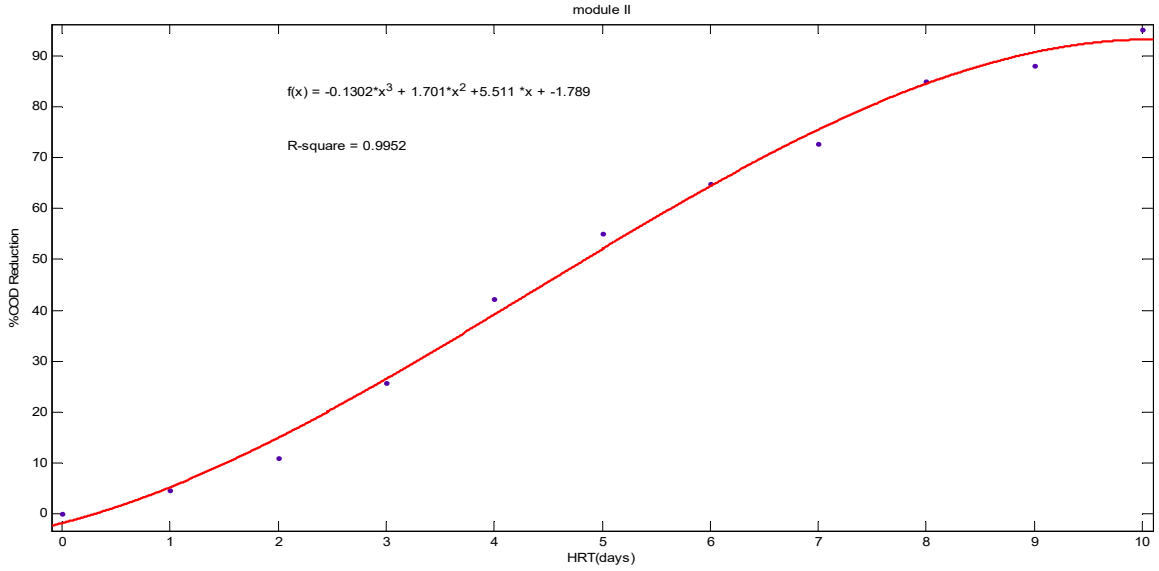


Figure 4.9 Plot of %COD reduction versus HRT (days) for module II

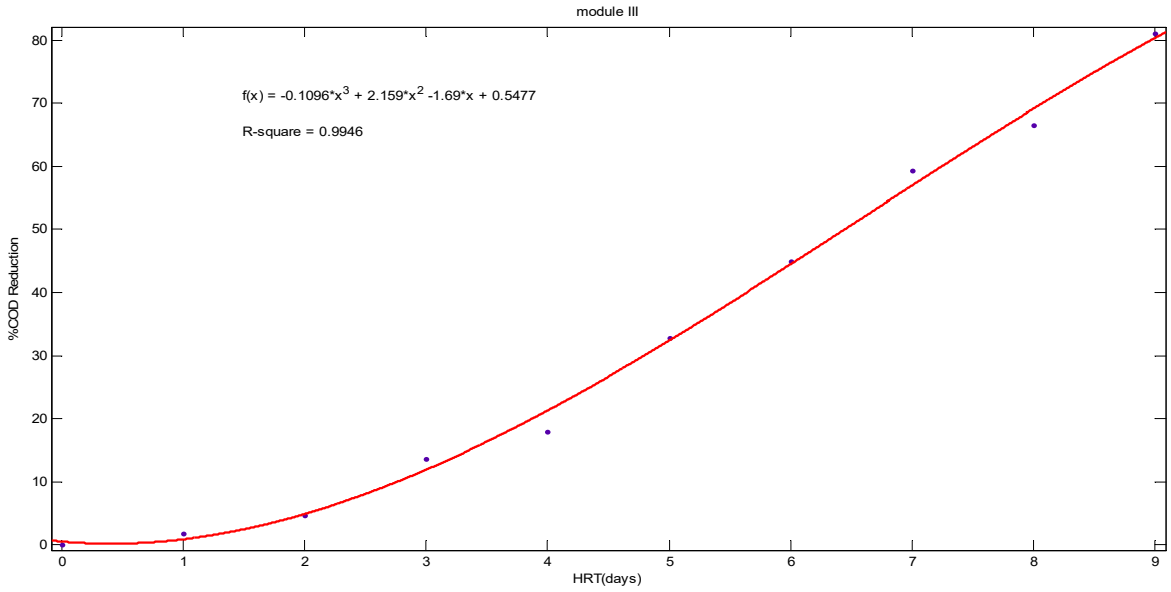


Figure 4.10 Plot of %COD reduction versus HRT (days) for module III

Figures 4.5, 4.6 and 4.7 show how the substrate COD of each reactor module reduced progressively with respect to time in days. The COD reduced from its initial value 120,320 mg/l to 24343 mg/l for module I; to 5775.4 mg/l for module II and to 23155.8 mg/l for module III at the HRT of 10 days. However, from figures 4.8, 4.9 and 4.10, we can see how the percentage COD (%COD) reduction increased with HRT (days) until the ninth (9th) day when it assumed its maximum of 79% and 80.8% for modules I and III, while the improvement continued for module II until the tenth (10th) day when it assumed its maximum of 95.2%. These graphs were plotted with R-square values of 0.9918, 0.9952 and 0.9946 for modules I, II and III, respectively. With these values, it becomes very obvious that module II (UBCSD) is the most efficient reactor amongst the three in terms of substrate stabilization capacity. Interestingly, the % COD reduction achieved in the UBCSD is in close proximity to the report given by Trosh and Holler

(2001) that the combination of a bioreactor and microfiltration allowed a high COD reduction of 95%.

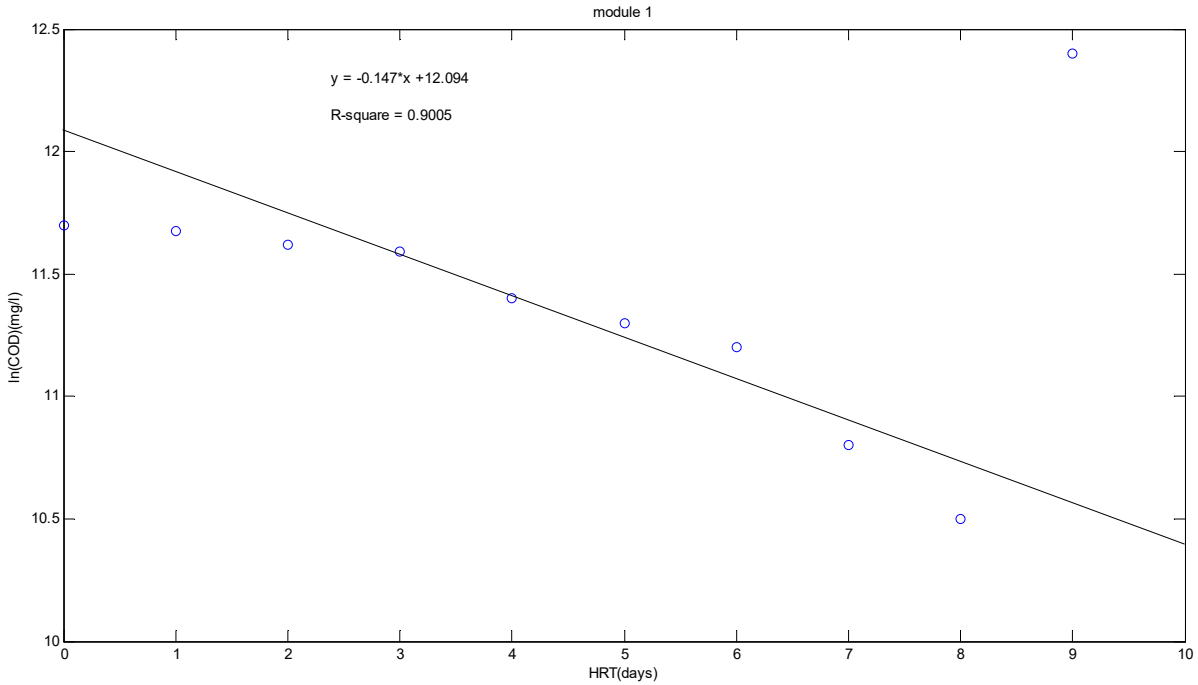


Figure 4.11 Plot of InCOD versus HRT (days) for module I

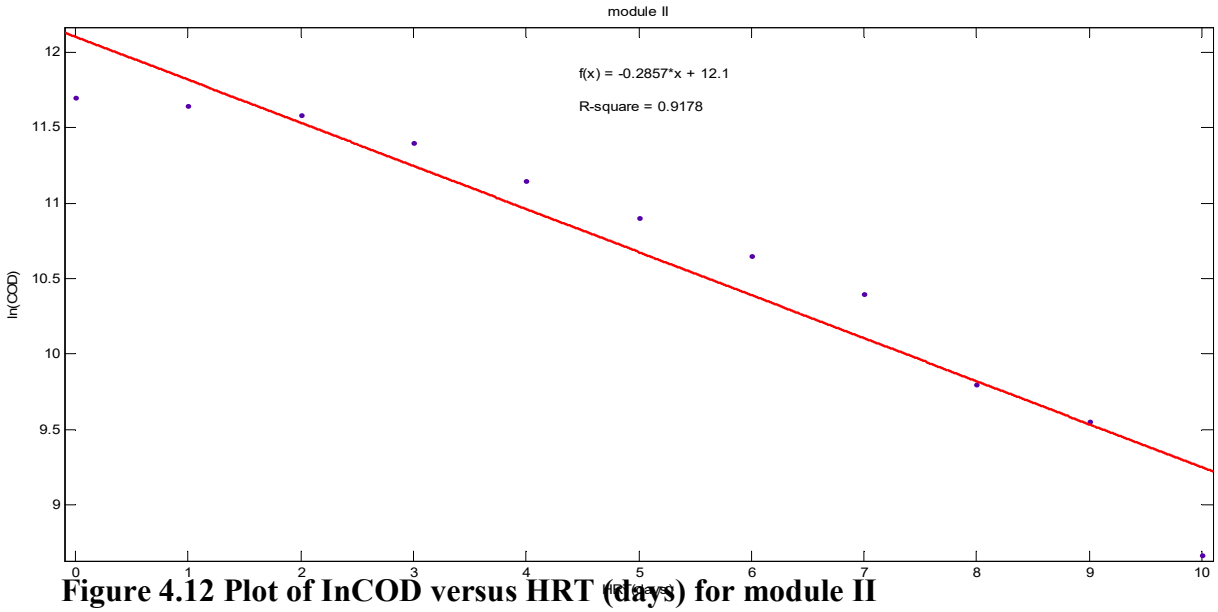


Figure 4.12 Plot of InCOD versus HRT (days) for module II

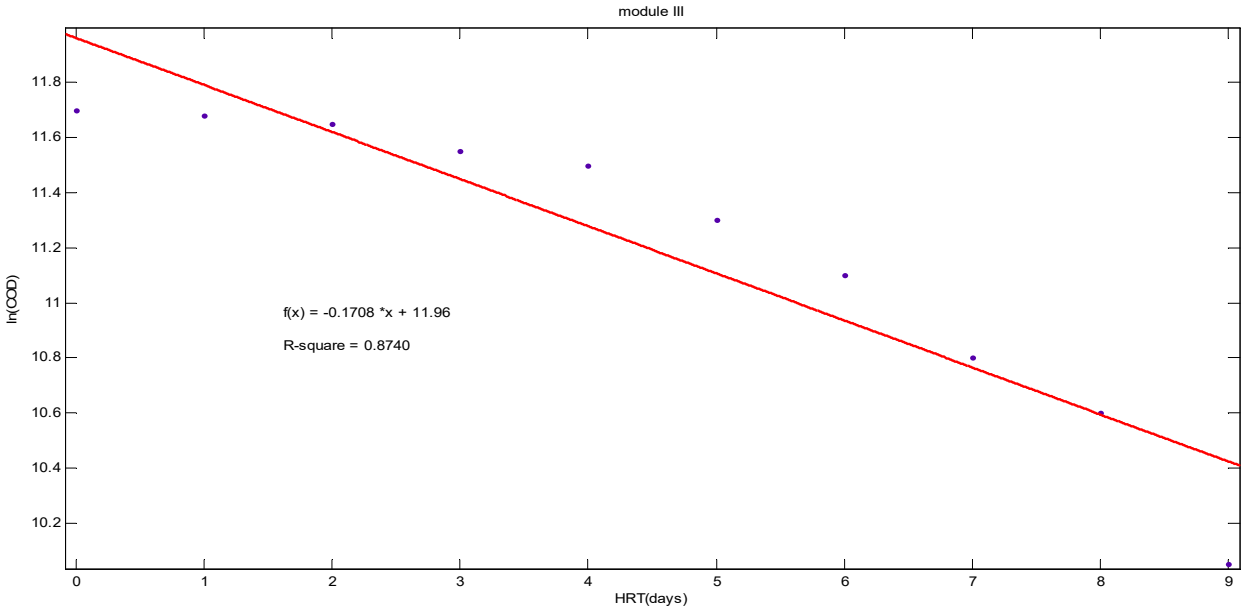


Figure 4.13 Plot of InCOD versus HRT (days) for module III

However, carrying out a MATLAB plot of ***InCOD*** versus HRT (days) using a linear regression approach, equations were generated for modules I, II and III as seen in figures 4.11, 4.12 and 4.13, respectively.These equations generated, closely conform to the model developed by Ghosh et al (2011) based on Fenton's reaction in first order kinetics, stated in **equation 3.15** in the previous chapter as:

$$InCOD(t) = -kt + InCOD(0). \qquad \ldots 4.10$$

These MATLAB plots were achieved with the R-square values of 0.9005, 0.9178 and 0.8740 for modules I, II and III, respectively.

4.3.5.1 Kinetic Parameters in *InCOD* plot versus HRT for Module I

The MATLAB plot of ***InCOD*** versus HRT (days) for module I (figure 4.11) gives the following equation:

$$y = -0.147x + 12.094 \quad \ldots 4.11$$

Where $y = InCOD(t)$, $x = t$ and $R\text{-square value} = 0.9005$ **…4.12**

Hence, substituting for y and x into equation 4.11, we have:

$$InCOD(t) = -0.147t + 12.094 \quad \ldots 4.13$$

Therefore, comparing equations 4.10 and 4.13, we have that:

$InCOD(0) = 12.094$ and $k = 0.147$.

4.3.5.2 Kinetic Parameters in *InCOD* plot versus HRT for Module II

The MATLAB plot of ***InCOD*** versus HRT (days) for module I (figure 4.12) gives the following equation:

$$f(x) = -0.2857x + 12.1 \quad \ldots 4.14$$

Where $f(x) = InCOD(t)$, $x = t$ and $R\text{-square value} = 0.9178$

Hence, substituting for $f(x)$ and x, we have:

$$InCOD(t) = -0.2857t + 12.1 \quad \ldots 4.3.7$$

Comparing equations 4.10 and 4.15, we have that:

$InCOD(0) = 12.1$ and $k = 0.2857$

4.3.5.3 Kinetic Parameters in *InCOD* plot versus HRT for Module III

The MATLAB plot of ***InCOD*** versus HRT (days) for module I (figure 4.13) gives the following equation:

$$f(x) = -0.1708x + 11.96 \quad \ldots 4.16$$

Where ***f(x) = InCOD(t), x = t*** and ***R-square value = 0.8740***

Hence, substituting for ***f(x)*** and ***x***, we have:

$$InCOD(t) = -0.1708t + 11.96 \quad \ldots 4.17$$

Comparing equations 4.10 and 4.17, we have that:

InCOD(0)= 11.96 and ***k = 0.1708***

However, comparing the graphical values of ***InCOD(0)*** which are ***12.094, 12.***1 and ***11.96*** for modules I, II and III, one can see that there is a close resemblance between them and the natural logarithm of the experimental value of the initial COD. The experimental initial COD value is given as:

$$COD(0)_{Exp} = 120320 \text{ mg/l}$$

Applying the natural logarithm of the experimental COD [$COD(0)_{Exp}$],we have:

$$In\ COD(0)_{Exp} = In120320 = 11.698 \quad \ldots..4.18$$

This close resemblance between the experimental and graphical values of initial COD, to a large extent, comes in handy in the validation of model equations 4.10

The values for the first order kinetic constant (***k***) of COD for modules I, II and III are 0.147, 0.2857 and 0.1708, respectively. ***k*** is an important parameter which is used as a measure of the rate at which the substrate COD is reduced and is found to be highest in module II (UBCSD) followed by module III (CSTR), and the least value was achieved in module I (UASB). A careful consideration, however, of the ***k-*** values obtained in relation to the

COD reduction achieved in each reactor, shows that substrate stabilization improves as ***k*** increases. Besides, since the effluent in the UBCSD was found to be more stabilized than was achieved in the UASB and CSTR, its sludge has the tendency of posing the least environmental threat. Therefore, it exhibits the capacity to generate effluent that can serve as better fertilizer than the other reactors.

4.3.6. OTHER MATLAB PLOTS

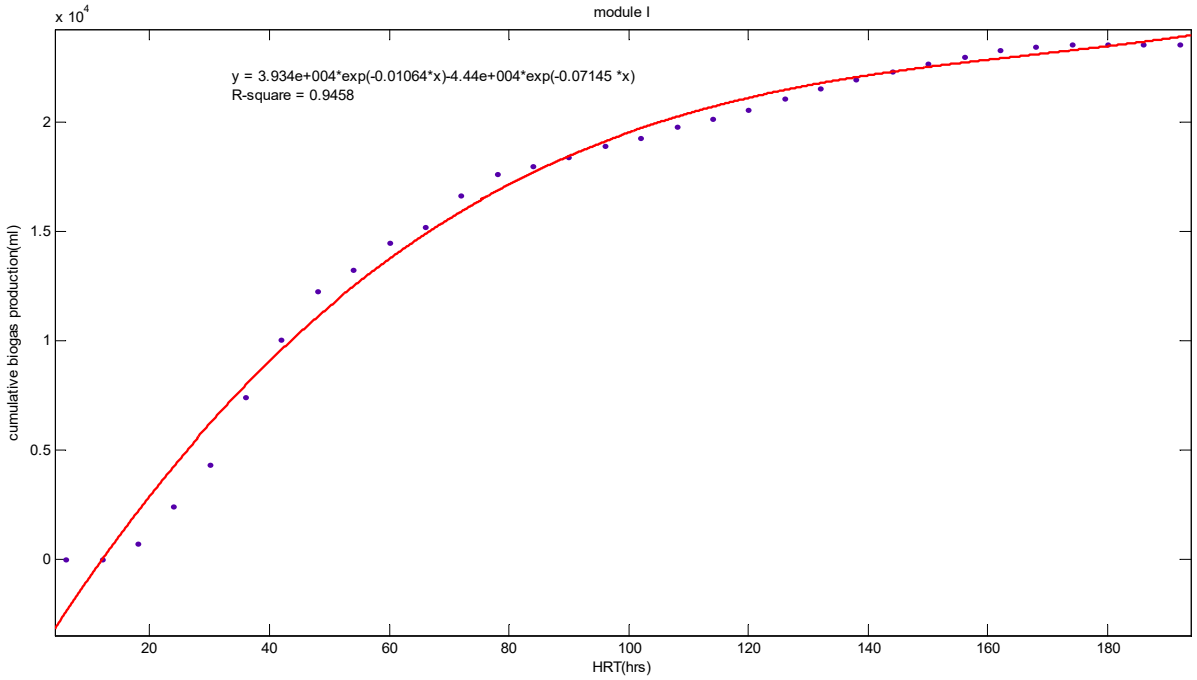


Figure 4.14 Plot of cumulative biogas production versus HRT (hours) for module I

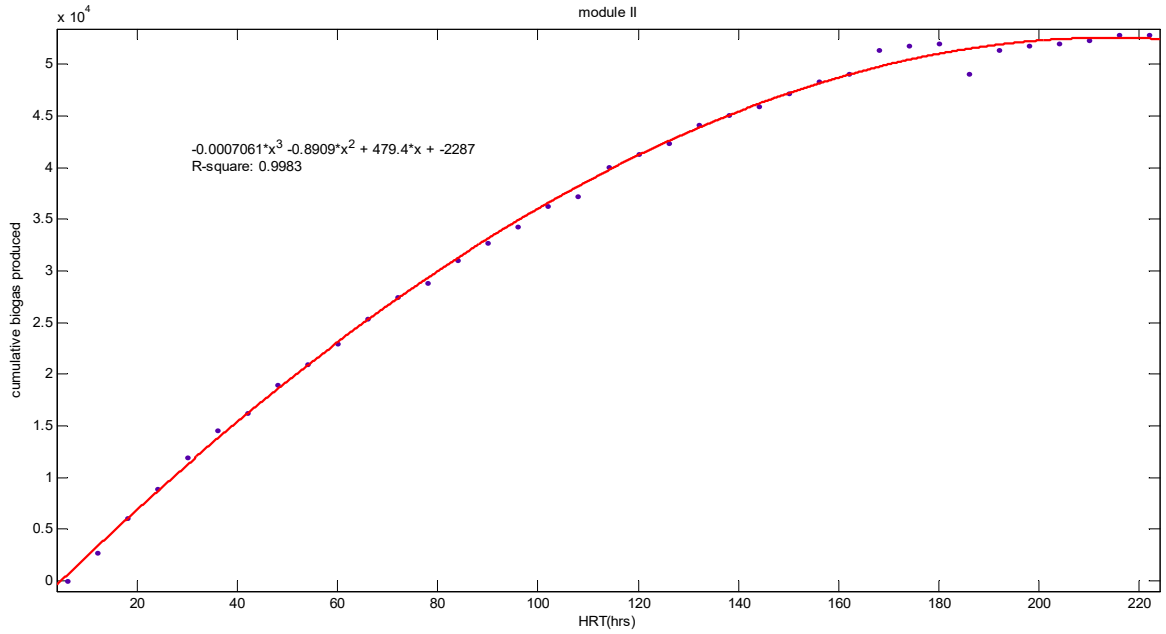


Figure 4.15 Plot of cumulative biogas production versus HRT (hours) for module II

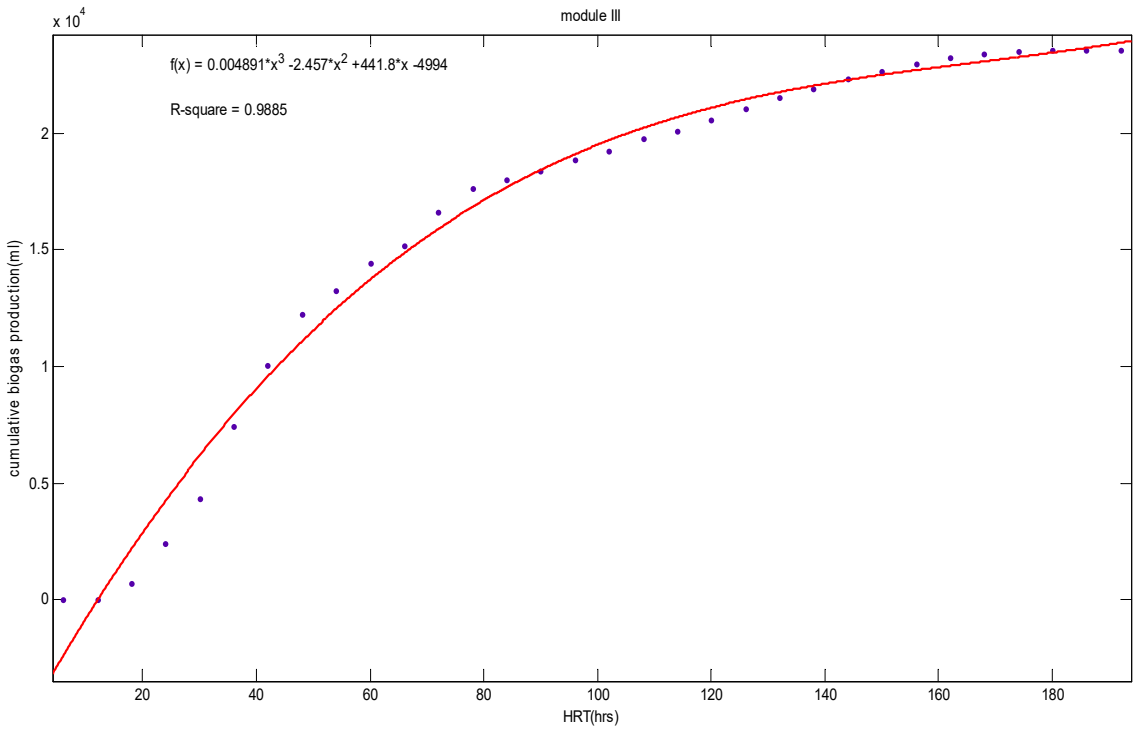


Figure 4.16 Plot of cumulative biogas production versus HRT (hours) for module III

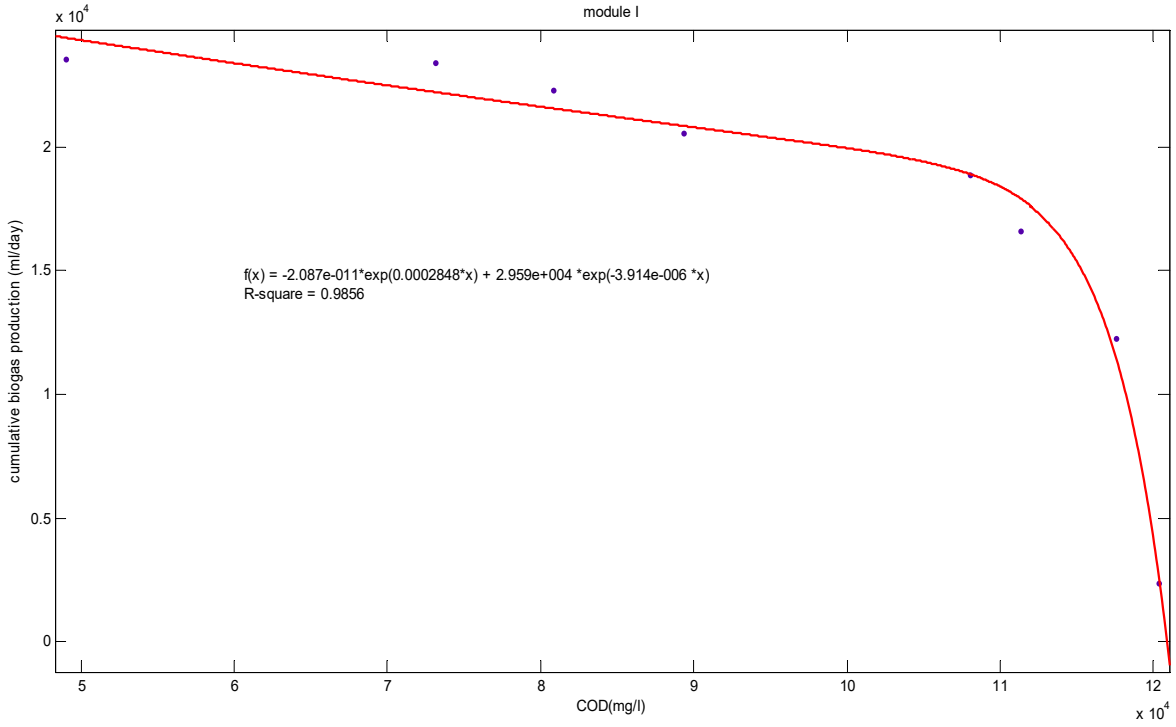


Figure 4.17 Plot of cumulative biogas production versus COD for module I

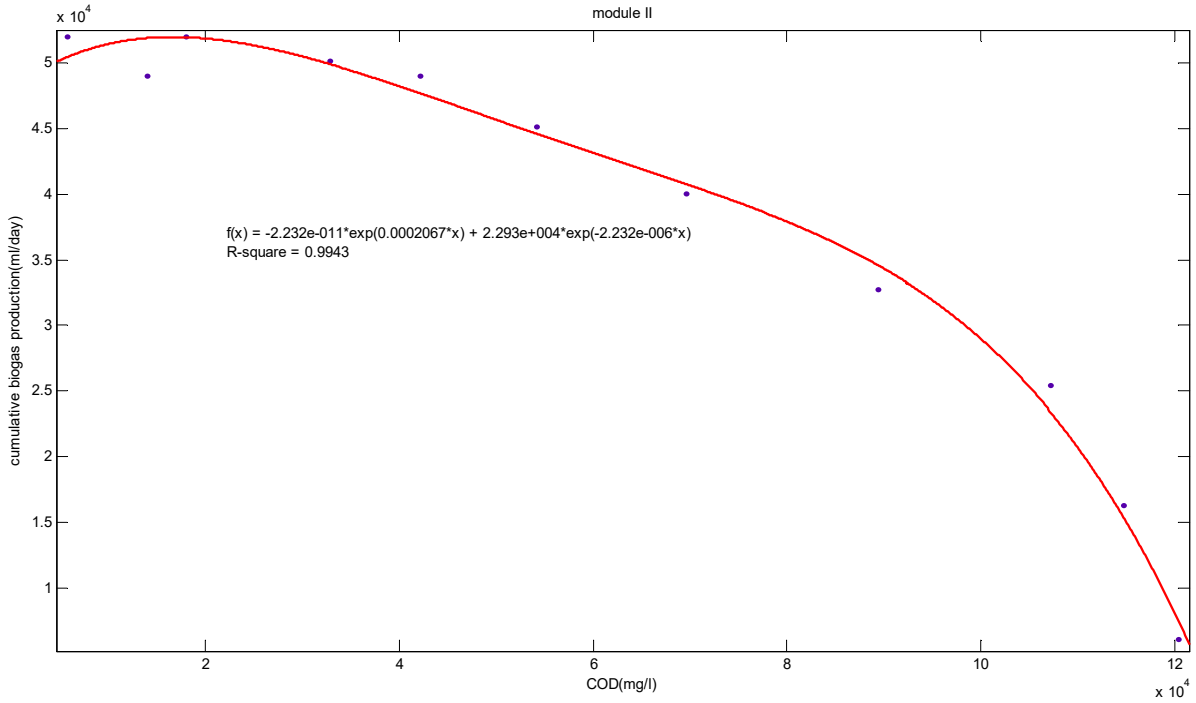


Figure 4.18 Plot of cumulative biogas production versus COD for module II

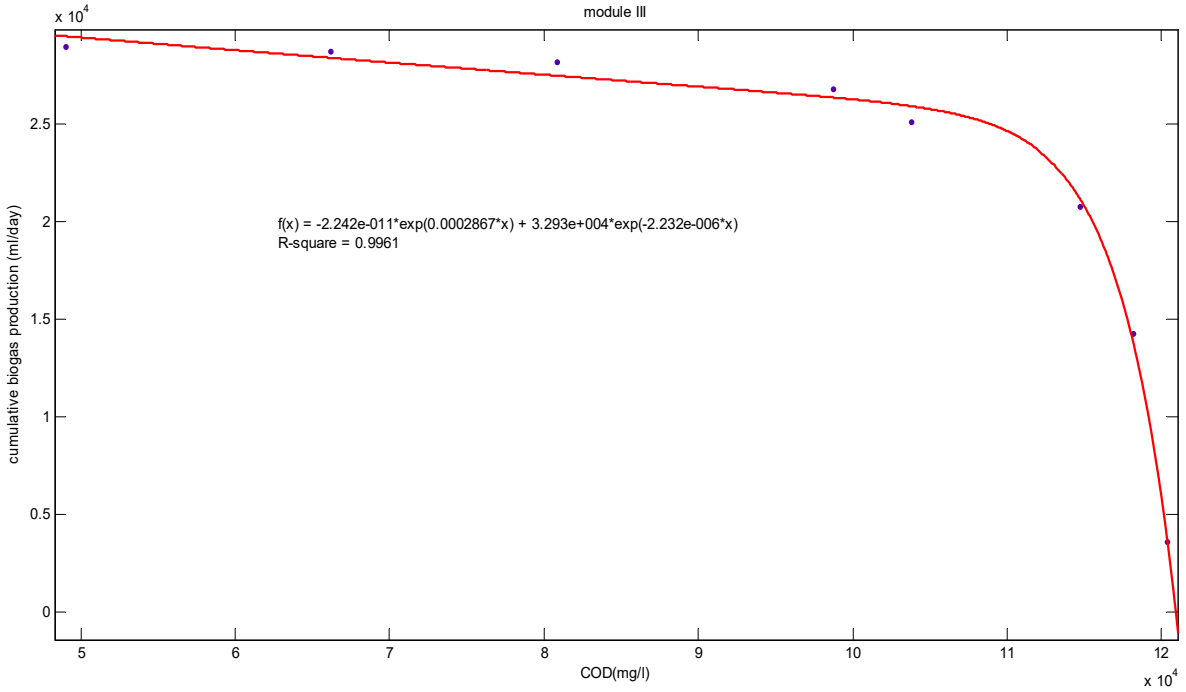


Figure 4.19 Plot of cumulative biogas production versus COD for module III

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1. CONCLUSION

The process performance of the three reactors in terms of COD removal and biogas generation profiles was discussed exhaustively in the previous chapter of this work. These reactors are: the upflow anaerobic sludge blanket (UASB) reactor, the upflow bioreactor with central substrate dispenser (UBCSD) and the continuous stirred tank reactor (CSTR). The flow features and configurations of the reactors as well as their attendant results were also carefully considered in the previous two chapters. It is worthwhile to note that these reactors were examined within an integrated assembly of these three bioreactors being operated at the same time and subjected to be under anaerobic conditions for the sole purpose of achieving a better comparative study of their performances.

Several steps were undertaken in order to prepare the bioreactor system for the actual experimental phase. The reactors were allowed to run without interruption for a hydraulic retention time (HRT) of 10-days and a mesophilic temperature of 37^0C. A recording of the biogas production was made in every six(6) hours and the biogas generated was at each set period liberated into the biogas collector tanks provided for this purpose. The COD level of the substrate was measured on a daily basis and the overall results achieved were tabulated in tables 4.1 to 4.7 while their analysis was exercised using figures 4.1 to 4.19.

With the aid of graphical analysis, the study concludes that among the three reactors, the UBCSD is the most superior and a promising technology as compared to UASB and CSTR for the treatment of organic municipal waste (OMW). The specific conclusions drawn from the studies are as under:

- UBCSD generated the highest level of biogas production cumulatively with the value of 52915 ml, while the values in the UASB and the CSTR were 23550 ml and 28980 ml, respectively as seen in table 16.
- UBCSD has the highest level of percentage COD removal of 95.2%, followed by module III, the CSTR (B4) with the value of 80.8%; while module I, the UASB (or B1), offered the lowest level of percentage COD removal of 79.0% as seen in figures 4.8, 4.9 and 4.10. With these values, it becomes very obvious that module II (UBCSD) is the most efficient reactor amongst the three in terms of substrate stabilization capacity.
- Realizing the fact that the UBCSD unit exhibits the smallest overall volume (see section 3.41 of chapter 3), and comparing the level of biogas generation in each of the reactors at the end of the experiment, it can conveniently be said that the biogas production achieved in the UBCSD is up to 50% more than that achieved in the CSTR and above 50% more than that achieved in the up-flow anaerobic sludge blanket reactor (UASB), respectively. The success accomplished in the UBCSD, is believed to be as a result of the central substrate dispenser (CSD) unit incorporated into the UBCSD which helped to generate an up-flow, cross-flow and down-flow pattern of the substrate for efficient mixing and maintenance of process stability.

- Percentage COD (% COD) reduction achieved in the UBCSD is in close proximity to the report given by Trosh and Holler (2001) that the combination of a bioreactor and microfiltration allowed for a high COD reduction of 95%.

From the results achieved, it is evident that the flow pattern of the UBCSD, in conjunction with the associated resultant effective mixing, helped immensely in the achievement of the recorded high level of performance within this module. Thus, the success accomplished in terms of biogas production and COD reduction, are in concord with the research findings published by Unger et al (2000), which stated that substrate flow and mixing in bioreactors have significant effect on the overall performance of the bioreactors.

5.2. RECOMMENDATIONS

The advances of anaerobic digestion (AD) technology have been supported by legislation. Most European countries are aiming to limit MSW disposal to landfills to no more than 5% of the collected material and have increased taxes on landfilling. This will ensure that waste is properly treated for combustibles and organics rather than being buried in the ground. The 15% renewable energy by 2010 target as well as schemes such as "green pricing" in The Netherlands and some other European countries allow AD facilities to sell biogas for electricity generation at a premium. Similarly, in the United Kingdom, under the Non- Fossil Fuel Obligation (NFFO) act, electricity is sold at a premium from AD system. Another factor that has triggered opting for energy recovery from waste is international agreements with respect to greenhouse gas emissions.

However, considering the importance of the treatment of MSW using anaerobic digestion (AD) technology; and having tested and proven the high efficiency and capacity of the UBCSD to help achieve this goal, the following recommendations are made:

i) The operating parameters of the digester such as temperature, speed of agitation, pH, organic loading rate (OLR), etc, must be optimized and controlled so as to enhance the microbial activity and thus increase the anaerobic degradation efficiency of the system.

ii) The municipal waste should undergo pretreatment by mechanical sorting or source separation. These separation techniques ensure removal of undesirable or recyclable materials such as glass, metals, stones etc. The removal of the inert fraction of MSW which contains stones, glass, sand, metal, etc prior to digestion is important as otherwise it increases digester volume and wear of equipment.

iii) The resultant material after separation (i.e. OMW which is the organic fraction of the MSW) should be dried in order to make it moisture-free for the sake of preserving it from unwanted degradation until such a time when slurry of it is required to be made and fed into the reactor for anaerobic digestion.

iv) The use of cow rumen content as inoculant is recommended because of its capacity to improve the microbial activities during the operation of the bioreactors.

v) During the experimental preparation, a dry mass of OMW was milled to a powdered form, generating a 500μm mesh size. Slurry of this powdered waste was made with which the reactors were loaded. However, during the experiment, it was observed that the substrate showed signs of having the capacity to clog the electromagnetic metering pumps. This situation is undesirable, for it is capable of causing the fouling of the digestion process with attendant negative results. So, a powdered OMW with a particulate size below 250μm is advised. This will solve the problem of

clogging of pump and at the same time increase the surface area of the feedstock, for an enhanced bacterial action on the substrate.

vi) Reliable pressure gauges are required to be mounted on the bioreactor vessels, so that the pressure levels of the biogas produced can be effectively monitored to avoid excessive pressure build up which can cause serious hazard. In addition, pressure relief valves can come in handy when connected to the biogas collectors to help prevent the occurrence of hazardous explosions during biogas collection.

vii) For a commercial scale consideration of the UBCSD, it is advisable to employ the use of multiple vessels connected in series or parallel with a common feeder tank, than to engage in the enlargement of a single vessel that may be exposed to the danger of exhibiting serious flow problems which may require the design of complicated parts in order to meet up with the substrate flow requirements.

5.3 CONTRIBUTION TO KNOWLEDGE

- The use of the Central Substrate Dispenser (CSD) in bioreactor technology for a double vessel upflow configuration, has in a very remarkable way proved to be highly effective for the improvement of the dynamics of the working substrate. Consequently, the enhancement of the substrate flow has paved way for the achievement of considerably high level of biogas production and waste stabilization. However, the secret behind the success of this new technology, is that the CSD assists immensely in the maintenance of substrate homogeneity; prevention of temperature gradient and fouling of the digestion process. These are problems that are usually associated with bioreactors, and if not properly handled, can cause poor biogas performance.
- The use of cow rumen contents as inoculants has been proven to be of considerable importance in the enhancement of biogas production and COD reduction. Biogas production lag phase (BPLP) has been reported to be 7 to 14 days (Budiyono et al, 2010); but from the experiments carried out, it was established that BPLP was 12 hours. This drastic reduction in BPLP, was as a result of improved microbial activities due to the use of the aforementioned method of inoculation.

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APPENDIXES

Table 1.1 Typical Biogas Composition

Methane	55-70% by vol.
Carbon dioxide	30-45% by vol
Hydrogen sulphide	200-4000 ppm by vol
Energy content of AD gas product	20-25MJ/standard m^3
Energy content of CH4 per ton MSW	167-373MJ/Ton MSW

(RISE-AT, 1998),

Table 2.1 Current and Planned Waste Legislation in Europe

Country	
Austria	**Aims to ban landfilling of more than 5% organics by 2004**
Belgium	**Soon to ban direct landfilling of combustible MSW**
Denmark	**Banning and landfilling of combustible MSW**
Finland	**Policies to encourage co-combustion of MSW with other fuels**
France	**Banning landfilling of combustibles by 2002.Landfill levy of 20FF/tone**
Germany	**Restricting landfilling of waste with more than 5% organic carbon content by 2005.**
Netherlands	**Landfilling of combustibles banned.Direct landfilling of other MSW banned by 2000.**
Sweden	**Decrease in reliance on landfill by increasing recycling rates and WTE rates.**
UK	**Recycling target of 25% by 2000. Lanfill tax of 7 pounds/tonne since 1996.**
Ireland	**Considering imposition of landfill tax.**
***Data source: The Bioreactor Landfill, A white paper from Waste Management, Inc. 2000**	

Table 2.2: The features of Chinese fixed dome, Indian floating cover and tube digesters.

Type of Digester	Configuration of Digester	Gas Collection Provision	Materials for Construction	Mixing/flow type
Chinese fixed dome	Cylindrical with a fixed upper dome cover	In-fixed dome	Clay, bricks and stones for the walls and dome	Mixed flow
Indian floating drum	Cylindrical with a partitioning wall and a metallic floating drum cap	In-floating metallic cap	Clay, bricks and stones for the walls, floating drum of metal	Increased mixed flow as a result of partitioning wall
Tube digester	Tube-like	External through a venting pipe	Polyethelene foil for digester wall and porcelain pipe for the inlet and outlet pipe	Slow axial flow

Table 2.3: Comparative analysis of Chinese fixed dome and Indian floating cover digesters

S/N	Item for Comparison	Chinese Fixed Dome	Indian Floating Drum
1	Gas storage capacity	Lower due to fixed dome space	Higher due to adjustable floating drum
2	Gas leakage problem	Leakage is high through outlet chamber and poor sealing provision	Lesser due to much lower gas pressure
3	Gas pressure	10 times higher, imposing more demanding constructional technique and precautions	Much lower, about 10cm water column
4	Efficiency of gas delivery to appliances	Poor due to constantly changing gas pressures	Better efficiency due to stable gas pressures by the floating drum cap mechanism
5	Construction cost	lower in ratio of 1:2.1	Higher due to floating drum cost
6	Overall efficiency	Lower	Higher

Table 2.4: Comparative construction costs of ADI and ADII

Constructional Material	ADI		ADII	
	Quantity	Amount (rupies)	Quantity	Amount (rupies)
Bricks	3000	1800	2750	1650
Cement	30 bags	1800	25 bags	1500
Coarse sand	$6m^3$	360	$3m^3$	360
Fine sand	$3m^3$	180	$3m^3$	180
Hard stone blast	$3m^3$	210	$2.5m^3$	175
Mason	30	900	25	750
Labour	60	600	50	500
		5850^h		5150^h

Table 2.5. Anaerobic Plants in various nations

Country	No. of plants in operation	No. of plants under Construction
Austria	10	0
Belgium	1	2
China	0	1
Denmark	21	1
Finland	1	0
France	1	0
Germany	30	9
India	0	4
Italy	2	4
Japan	0	1
Netherlan	4	0
Poland	0	1
Spain	0	1
Sweden	7	2
Switzerla	9	1
Thailand	0	1
UK	0	1
Ukraine	1	0
USA	1	2

Data Source: IEA Bioenergy AD Activity 1997 Report, Systems & Markets

Table 2.6. Companies supplying AD plants of capacity >2,500 tons/year

Company	No. of plants in operation	No. of plants under construction
Arge Biogas, (Austrian)	2	0
Entech,(Austrian)	7	4
Kompagas,(Swiss)	10	0
OWS-Dranco,(Belgian)	4	1
BTA,(German)	11	0
Steinmuller Valorga, Sarl (French)	2	4
Ecotec,(Finish)	1	7
C.G. Jensen,(Danish)	1	0
BWSC,(Danish)	3	0
NNR,(Danish)	6	0
Kruger,(Danish)	12	2
Bioscan, ,(Danish)	1	1
Prikom/HKV,(Danish)	2	0
Jysk, ,(Danish)	1	0
Citec, ,(Finish)	1	1
Linde-KCA,(German)	1	0
Schwarting UDHE, (German)	1	0
ANM, (German)	1	0
Haase Energietechnik, (German)	1	1
DSD Gas und Tankanlagenbau, (German)	2	0
IMK BEG Bioenergie, (German)	0	1
Bioplan, (Danish)	1	0
TBW, (German)	1	0
BRV Technologie Systeme, (German)	2	0
D.U.T. (German)	1	0
Paques Solid Waste Systems, (Dutch)	3	1
Unisyn Biowaste Technology,(USA)	1	0
Duke Engineering, (USA)	0	2
WMC Resource Recovery, (UK)	0	1
R.O.M. (Swiss)	1	1
Purac, (Swedish)	1	0
SWECO/VBB, (Swedish)	0	1
NSR, (Swedish)	1	0
BKS Nordic, (Swedish)	1	0
Projectror, (Swedish)	2	0
Biocel/Heidermij Realisatie,(Dutch)	1	0
Ionics Italba,(Italian)	1	0
Kiklos, (Italian)	2	0
SPI, (Italian)	1	0
RPA, (Italian)	1	0
Data Source: IEA Bioenergy AD Activity 1997 Report, Systems & Markets Overview of AD		

S/N	Components	Amount by weight
1	Glass	2.7
2	Organic fraction	58
3	Paper	5.6
4	Plastics	2.3
5	Stones	1.4
6	Straw and woody substances	30

Table 3.1. Content of Municipal Solid Wasted (MSW) source from Owerri Central Market.

Table 3.2. Limiting concentration for various inhibitors of biomethanation.

Substance	(mg/l)
Copper	10-250
Calcium	800c
Sodium	800c
Magnesium	300c
Nickel	I00-1000
Zinc	350-1000
Chromium	200-2000
Sulfide (as sulfur)	200
Cyanide	2

Table 4.1. Biogas Production in Module I – UASB (B1)

S/N	TIME (hrs)	BIOGAS PRODUCED	CUMULATIVE BIOGAS
1	6	0,00	0,00
2	12	0,00	0,00
3	18	700	700
4	24	1700	2,400
5	30	1920	4,320
6	36	3100	7,420
7	42	2640	10,060
8	48	2200	12,260
9	54	1000	13,260
10	60	1200	14,460
11	66	720	15,180
12	72	1440	16,620
13	78	1000	17,620
14	84	375	17,995
15	90	375	18,370
16	96	525	18,895
17	102	375	19,270
18	108	500	19,770
19	114	350	20,120
20	120	450	20,570
21	126	500	21,070
22	132	450	21,520
23	138	400	21,920
24	144	400	22,320
25	150	350	22,670
26	156	300	22,970
27	162	300	23,270
28	168	150	23,420
29	174	100	23,520
30	180	30	23,550
31	186	0	23,550
32	192	0	23,550

Table 4.2. Biogas Production in Module II – UBCSD (B2 & B3)

S/N	TIME (HRS)	BIOGAS PRODUCTION IN B2 (ML)	CUMULATIVE BIOGAS (ML)	BIOGAS PRODUTION IN B3 (ML)	CUMULATIVE BIOGAS (ML)	CUMULATIVE BIOGAS B2+B3 (ML)
1	6	0	0,00	0,00	0,00	0,00
2	12	0	0,00	0,00	0,00	0,00
3	18	2,750	2,750	0,00	0,00	2,750
4	24	1,850	4,600	1,500	1,500	6,100
5	30	1,400	6,000	1,450	2,950	8,950
6	36	1,750	7,750	1,250	4,200	11,950
7	42	1,050	88,00	1,600	5,800	14,600
8	48	1,000	9,800	700	6,500	16,300
9	54	1,200	11,000	1,500	8,000	19,000
10	60	1,000	12,000	1,000	9,000	21,000
11	66	1,000	13,000	1,000	10,000	23,000
12	72	1,130	14,130	1,300	11,300	25,430
13	78	770	14,900	1,300	12,600	27,500
14	84	850	15,750	500	13,100	28,850
15	90	1,130	16,880	1,100	14,200	31,080
16	96	870	17,750	800	15,000	32,750
17	102	750	18,500	850	15,850	34,350
18	108	1,150	19,650	750	16,600	36,250
19	114	350	20,000	600	17,200	37,200
20	120	2,250	22,250	600	17,800	40,050
21	126	750	23,000	550	18,350	41,350
22	132	500	23,500	550	18,900	42,400
23	138	1,250	24,750	500	19,400	44,150
24	144	500	25,250	500	19,900	45,150
25	150	250	25,500	500	20,400	45,900
26	156	1,000	26,500	300	20,700	47,200
27	162	750	27,250	400	21,100	48,350
28	168	250	27,500	500	21,600	49,100
29	174	750	28,250	400	22,000	50,250
30	180	750	29,000	400	22,400	51,400
31	186	150	29,150	250	22,650	51,800
32	192	150	29,300	130	22,780	52,080

33	198	150	29,450	70	22,850	52,300
34	204	550	30,000	55	22,905	52,905
35	210	10	30,010	0	22,905	52,915
36	216	0	30,010	0	22,905	52,915
37	222	0	30,010	0	22,905	52,915

Table 4.3. Biogas Production in Module III CSTR (B4)

S.NO	TIME (HRS)	BIOGAS PRODUCTION (ML)	CUMULATIVE BIOGAS PRODUCED (ML)
1	6	0,00	0,00
2	12	0,00	0,00
3	18	1,600	1,600
4	24	2,000	3,600
5	30	2,400	6,000
6	36	2,800	8,800
7	42	3,200	12,000
8	48	2,300	14,300
9	54	2,660	16,960
10	60	1,140	18,100
11	66	1,100	19,200
12	72	1,600	20,800
13	78	1,200	22,000
14	84	800	22,800
15	90	1,200	24,000
16	96	1,120	25,120
17	102	880	26,000
18	108	400	26,400
19	114	200	26,600
20	120	200	26,800
21	126	500	27,300
22	132	400	27,700
23	138	300	28,000
24	144	200	28,200
25	150	250	28,450
26	156	200	28,650
27	162	50	28,700
28	168	50	28,750
29	174	50	29,800
30	180	180	28,980
31	186	0,00	28,980

32	192	0,00	28,980

TABLE 4.4. CHEMICAL OXYGEN DEMAND (COD) REMOVAL IN UASB (B1)

TIME (DAYS)	COD (Mg/l)	PERCENTAGE COD REMOVED
0	120,320	0%
1	117,552	2.30%
2	111,301.70	7.50%
3	108,012.30	10.20%
4	89,321.70	25.80%
5	80,821	32.80%
6	73,130.40	39.20%
7	49,020.80	59.30%
8	36,315.50	69.80%
9	24,343.00	79%
10	24,343.00	79%

TABLE 4.5. CHEMICAL OXYGEN DEMAND (COD) REMOVAL IN UBCSD (B2 & B3)

TIME (DAYS)	COD REDUCTION (Mg/l)	PERCENTAGE COD REMOVED
0	120,320	0%
1	114,641	4.70%
2	107,158.00	10.90%
3	89,321.70	25.80%
4	69,563.80	42.20%
5	54,176	55.00%
6	42,192.60	64.90%
7	32,859.60	72.70%
8	18,033.70	85.00%
9	14,044.70	88%
10	5,775.40	95.20%

TABLE 4.6. CHEMICAL OXYGEN DEMAND (COD) REMOVAL IN CSTR (B4)

TIME (DAYS)	COD (Mg/l)	PERCENTAGE COD REMOVED
0	120,320	0%
1	118,154	1.80%
2	114,691.40	4.70%
3	103,777.00	13.70%
4	98,715.80	18.00%
5	80,822	32.80%
6	66,171.20	45.00%
7	49,020.80	59.30%
8	40,134.80	66.60%
9	23,155.80	81%
10	23,155.80	81%

TABLE 4.7. Cumulative Biogas Produced with time (DAYS) in the three Reactors.

TIME (Days)	CUMMULATIVE BIOGAS PRODUCTION		
	MODULE I B1(ml)	MODULE II B2 & B3 (ml)	MODULE III B4 (ml)
1	2,400	6,100	3,600
2	12,260	16,300	14,300
3	16,620	25,430	20,800
4	18,895	32,750	25,120
5	20,570	40,050	26,800
6	22,320	45,150	28,200
7	23,420	49,100	28,750
8	23,550	52,080	28,980
9	23,550	52,915	28,980
10	23,550	52,915	28,980

Table 4.8. Kinetic parameters from modified Gompertz model equations.

REACTOR TYPE	Biogas Potential, B_{max} (ml)	Biogas Production Rate, R_b (ml/d)	Biogas Production Lag Phase , λ	Goodness of fit (R^2) value
Module I (B1)	23620	8014.03	0.45	0.9981
Module II (B2 and B3)	53440	9148.93	0.18	0.9926
Module III (B4)	28740	9972.9	0.57	0.9989

Table 4.9. Kinetic parameters in *InCOD* plot versus HRT(days)

BIOREACTOR TYPE	Goodness of fit (R-square) Value	Natural logarithm of initial COD [In COD(0)]	First order kinetic constant (k)
B1 (UASB)	**0.9005**	**12.094**	**0.147**
B2&B3(UBCSD)	**0.9178**	**12.100**	**0.2857**
B4 (CSTR)	**0.8740**	**11.960**	**0.1708**