Hand Driven Energy Efficient Reactor for Biogas Production from Organic Solid Waste

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Abstract

Pakistan faces annual rise of 3.4% in waste generation with organic waste being the major portion; leading to unhygienic environment and communicable diseases. Conventional treatments (landfill and incineration) are expensive and inefficient with respect to energy or process - apart from being the leading causes of greenhouse-gas emissions in waste sector. Anaerobic digestion is thus the most promising method available. Anaerobic digester decomposes organic waste (kitchen waste, leaves, manure, sludge, and other organic waste) into renewable energy i.e. biogas (potentially utilized for cooking and electricity generation). Dry anaerobic digester operated under mesophilic conditions with 100 litres capacity was designed for the project. The purpose of the project was to create an energy efficient, eco-friendly digestion device efficient in cutting down landfill waste, greenhouse gas emissions and providing sufficient biogas for cooking purposes (at homes, offices, mess, and industrial level). Intermittent mixing was ensured by installing a manual mixer. Moreover, water jacket of the reactor was designed to use thermosiphon principle for maintaining mesophilic conditions. Kitchen waste from hostel mess and student cafeteria of NUST was used as substrate. Further, for start-up of the reactor fresh cow dung and slurry were used as inoculum (1:1) ratio with the selected feedstock. At start-up phase, the reactor was operated in batch mode for 45 days. A daily feed of 2 to 3 kg of kitchen waste will be fed to produce about 200 liters of biogas i.e. sufficient for 1 hr of cooking.

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List of Abbreviations

AD	Anaerobic Digestion
NUST	National University of Sciences and Technology
C/N	Carbon to Nitrogen ratio
KWH	Kilo Watt Hour
MC	Moisture Content
MSW	Municipal Solid Waste
MW	Molecular Weight
OFMSW	Organic Fraction of Municipal Solid waste
OLR	Organic Loading Rate
OM	Organic Matter
RT	Retention Time
STP	Standard Temperature Pressure
SWM	Solid Waste Management
TOC	Total Organic Carbon
TKN	Total Kjeldahl Nitrogen
TS	Total Solids
VFA	Volatile Fatty Acids
VS	Volatile Solid

Introduction

1.1 Background

Municipal waste is an ever growing problem, having direct relation with the increment in the population and improvement in socio – economic status. Pakistan is a developing country with waste generation rate of about 47.9 kilo tons of waste per day, with 3.4% of annual rise (Agency, 2005). Like many other developing countries, major fraction of Pakistan's household waste is biodegradable i.e. around 40-60%. Due to poor waste management, most of the waste is either disposed by crude burning or open dumping. Unfitting management and disposal of waste causes all sorts of environmental, economic, and health problems. Above all, the release of Green Houses Gases (GHG) like methane and carbon dioxide cause adverse climate effects and increment in annual temperature. Therefore, adequate disposal of biodegradable waste is must.

Most regarded treatment option for biodegradable waste is anaerobic digestion. As such waste contains high moisture content (85 -90%) and low calorific value, which makes its incineration unfeasible. Above all, incineration method causes air pollution by releasing nitrogen dioxide, sulphur dioxide, and other GHGs. Anaerobic digestion reduces air pollution along with the recovery of nutrient, energy, and compost. Overall, AD is an efficient net energy producing system (Edelmann, 2005).

During last two decades, treatment of municipal organic waste through anaerobic digestion has gained much attention. Anaerobic digestion is a process of decomposition of organic waste in the anoxic and hypoxic conditions i.e. absence or lack of oxygen. Presence of different species of microorganisms play critical role in the decomposition and leads to the production of biogas and leachate as an end-product (Mahar et al., 2007). Production of biogas as fuel and use of leachate as organic fertilizer make AD a sustainable disposal option.

In the early days, AD was mainly used to treat domestic and animal waste, but later evolved to treat industrial waste and sludge. AD process throughout its history has evolved, encompassing the treatment of mix waste eg: animal waste + organic waste, sludge + paper water, and others (Dewil, Appels, Baeyens, & Degre, 2008).

AD is generally categorised as dry (TS > 10%) or wet (TS < 10%) , single or two stage system, mesophilic (temperature < 35 -40%) or thermophilic (temperature >55%) or continuous or batch phase process (Yabu, Sakai, Fujiwara, Nishio, & Nakashimada, 2011). However, better efficiency and energy recovery has been reported for dry digestion. Dry digestion has several advantages over wet; less working volume required, reduced water consumption, concentrated leachate (Bauer, Mayr, Hopfner-sixt, & Amon, 2009). Similarly, most of commercial plants under operation are single stage systems. Although, thermophilic system has faster decomposition rate but is lower stability compared to mesophilic conditions (Bouallagui et al., 2004).

1.2 Problem statement

Kitchen waste is a highly nutritive value part of the municipal waste's organic fraction with high efficacy of methane production. In most of areas due to poor collection, segregation and treatment facilities, kitchen waste is usually dumped openly leading to health hazards and outbreak of diseases. As, kitchen waste is highly putrescible, it attracts disease causing vectors, rodents, viruses, etc. resulting in spread of infections, allergies, diarrhea, malaria, and others. Moreover, inadequate waste management like crude burning, open dumping triggers numerous adversative consequences. Such as, surface, soil, and groundwater pollution through leachate but also encourages the growth of disease causing vectors. Furthermore, it reeks and emanates methane causing global warming. As, methane is 21 times more potent GHG gas.

The design and performance of anaerobic digestion is largely dependent upon the design of reactors, feedstock characteristics, and operation conditions. Physio-chemical characteristics of organic wastes also play critical role in the stability of Anaerobic digestion process and biogas production. Such parameters include particle size (10mm usually), total solids (TS), moisture content (MC), biodegradability, and volatile solids (VS). The biodegradability is specially an important parameter that estimates the rate of AD process completion. As, biodegradability of a substance is specified by methane yield or production of biogas and percentage of solids available i.e. total solids or total volatile solids so to be decomposed in the anaerobic digestion (Bauer et al., 2009). Volatile solids account for maximum biogas generation at a given temperature if, optimum conditions provided.

Reactor designs should be modified as per waste composition variation and operational parameters' choice. Such parameters involve solid contents (TS and VSS), retention time (RT or HRT), recirculation, mixing, , temperature, and others. Also, requirements of nutrients by microbes affects the anaerobic digestion process as; deficient nutrients may result in unfinished and unstable decomposition of the organic feed or wastes. Thus, causing failure of digester (Chaudhary, n.d.)

In this study, modification of the reactor design and the optimization of operational conditions has been conducted.

1.3 Objectives of the study

The key objectives are to promote dry anaerobic digestion technology as a sustainable and organic waste minimizing technology.

The definite objectives are as follow:

1. Design and troubleshooting of pilot scale hand driven and energy efficient reactor for dry anaerobic digestion
2. Start-up and operation of the designed reactor

1.4 Scope of the study

- Sabzi Mendi I9 Islamabad, NUST cafeteria and Hostel Mess were the venue and facilities opted for the collection of organic waste.
- At start-up phase, the reactor was operated in semi-continuous mode for 45 days, as a dry AD system i.e. having high solids
- Cow dung and slurry were used as Inoculums in the 1:1
- The reactor was operated at $38^{o}C$ temperature with particle size of around 10 mm (shredded manually) using grinder
- operational parameters and waste characteristics along with digestate's were analysed in IESE laboratory, NUST

2 Literature review

2.1 Introduction

To treat the growing problem of municipal waste, especially the 40-60% fraction i.e. organic (OFMSW), anaerobic digestion is considered as best option available. AD process is a sustainable system as it produces clean energy (biogas) along with treating organic waste. Furthermore, the digestate i.e. digestion residues attained can potentially be utilized as organic fertilizer, liquid fertilizer (slurry), or as soil amendment. AD is of two sorts i.e. wet digestion and dry digestion, based upon the solid content of the waste. Compared to wet AD, dry AD has been under the focus due to its relative benefits. Dry AD can handle high organic loading rate offered with smaller working volume, higher solid contents allow lesser water addition thus, lesser Pre-treatment. Dry AD also allows higher biogas yield rate and lesser post treatment of Digestate such as dewatering than that of wet AD. Above all, the low water content and smaller working volume in dry digesters utilize less energy for heating. Thus, making it sustainable and energy efficient system.

In this chapter, various aspects of solid waste system in Pakistan are discussed. Such aspects include wastes generation status, waste characteristics, disposal approaches for MSW, inclusive anaerobic digestion process review for treating OFMSW, energy potential of MSW, and optimization of parameters affecting dry AD are discussed.

2.2 Solid waste generation and its characteristics in Pakistan

Pakistan generates about 47920 tons or 47.92 kilo-tons of solid waste per day with 19190 tons of waste incorporated as urban waste and 28730 tons as rural waste (Agency, 2005). In Pakistan, an average municipal waste generation is approximated to be 1.89 to 4.29 (kg/house/day) or 0.68 to 0.78 (kg/capita/day), which varies according to the economy and lifestyle of the citizens respectively (Ismail & Manaf, 2013). Pakistan has no proper solid waste management system due to which even 50% of collecting waste pose an immediate burden on the waste disposal sites. Most of the uncollected waste is either being burnt openly, dumped into ponds, water bodies and flood plains, or dumped in dumping sites which are no longer suitable for waste to dispose as they are not engineered and properly designed all these disposal practices are being done without any pre-or post-treatment except the separation of recyclable items by scavengers.

Following the trend of many other developing countries such as India, Srilanka, and Bangladesh, major portion of Pakistan's solid waste is organic waste i.e. 54% - 64% of the total waste. Organic waste is dense and corrosive**,** constituted of leftover food, wood, process residues and yard waste(Wilson, Rodic, Scheinberg, Velis, & Alabaster, 2012). Pakistan being an agriculture major country and use of fresh food over canned food contributes to organic waste. While the remaining portion of the total waste contains agricultural waste (pesticides, fertilizers), industrial waste, plastic, paper, and several others.

2.3 Potential problems associated Solid waste

Adequate disposal and treatment of MSW is one of the most potent problems faced by local governments or municipalities globally. waste generation rate or status faces annual increment due to several factors. Such as, increasing population, changing life styles, and consumption of products is posing serious threat to human and environment in most adverse way (Assamoi & Lawryshyn, 2012). Furthermore, in developing countries such as Pakistan such threats are exacerbate due to inadequate disposal practices like open dumping and crude burning.

Globally the most opted methods for waste handling is landfilling and incineration, but these practices have negative effects on the environment. The problems associated with landfills, include adequate site location, groundwater contamination and contribution to global warming. Furthermore, the build-up of organics, emanating gases, and plastic have caused the outbreaks of fire (Chaudhary, n.d.). Thermal treatment (incineration) of waste often receives disapproval because it imperils the environment and human health as, it is discordant with the very concept of 3Rs i.e. reducing, reusing, and recycling (Assamoi & Lawryshyn, 2012). Therefore, it is necessary to advance for alternative treatment options and methods. But several parameters like location of the sites, characteristics of waste, land accessibility, etc. influence the implication of alternatives. Anaerobic digestion of OFMSW is considered a recycling and most recommended method before landfilling. As, it can potentially extend the landfill life up to 20-40 years. Above all, AD contributes global warming reduction. The carbon content present in the organic fraction of the waste is a constituent of the carbon-cycle; as, combustion of biogas turn down the global carbon accumulation unlike fossil fuels. It releases carbon that had been removed by plants from the atmosphere during their lifespan (Fellowship, n.d.).

2.4 AD process description

AD is a process of decomposition of organic waste in the anoxic and hypoxic conditions i.e. absence or lack of oxygen.. It is a complex biochemical process, involving four major steps, shown below:

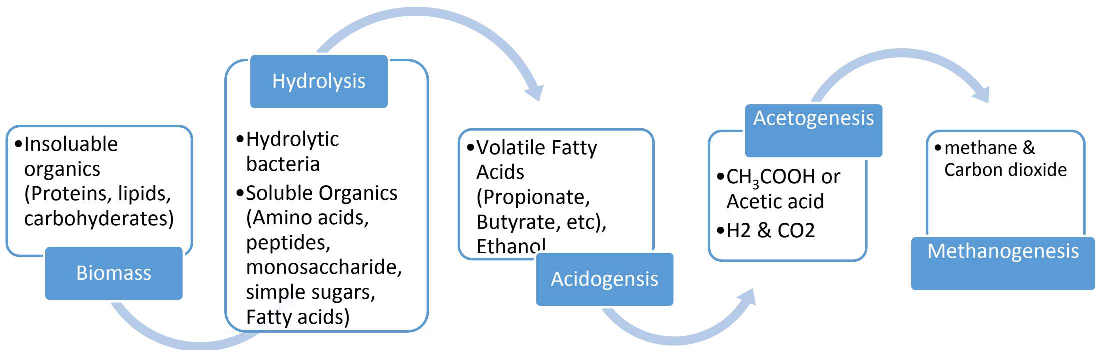

Figure 1: AD process

2.4.1 Hydrolysis

It is the very first step that occurs in AD. Addition of water breaks down the chemical bonds thus, serving as the cleavage. It serves as a precursor for the flow-up steps as, Hydrolysis with the help of hydrolytic microorganisms breaks down the complex organic molecules (protein, fat, and carbohydrates) in simpler ones (peptides, Amino acids, monosaccharide, Fatty acids, and others). Therefore, is a rate limiting parameter. Hydrolytic microorganisms (their activity rate and growth logarithm), temperature, and pH – all affects the Hydrolysis as a process.

In the case of a carbohydrate, monosaccharide is out turned upon the breakdown of polysaccharide (complex sugar). figure 2 illustrates the breakdown of disaccharide sugar i.e. lactose into its primary constituents glucose and galactose.

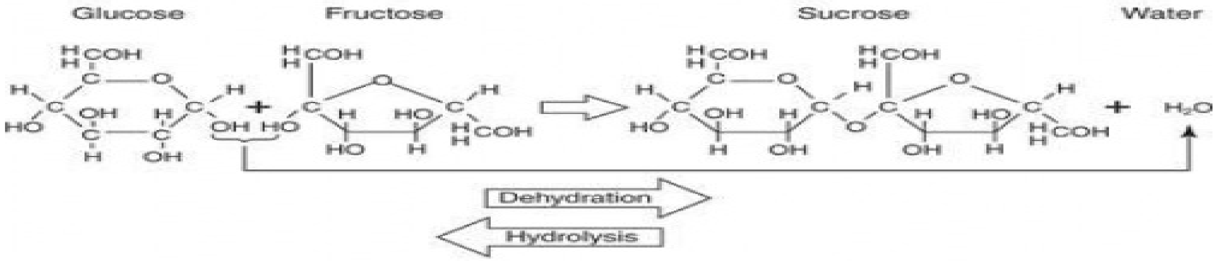

Figure 2 Breakdown of polysaccharide (complex sugar)

Source: (Rea & Slocum, 2014)

one example of the lipids (fats) hydrolysis is the breakdown of triglycerides. Upon the addition of 3 water molecules triglyceride's chemical bond is fragmented into glycerol and three fatty acids as, exemplified in figure 3:

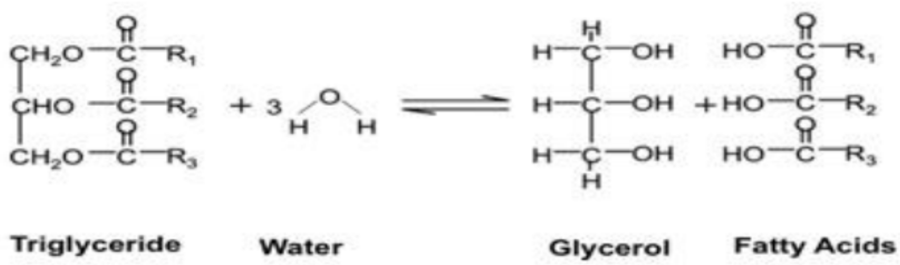

Figure 3:Breakdown of lipids
Source: (Rea & Slocum, 2014)

Proteins also undergo hydrolysis so to be broken down into its simpler constituents. As an example; peptide bonds splits into its subunits amino acids. figure 4 exemplifies that:

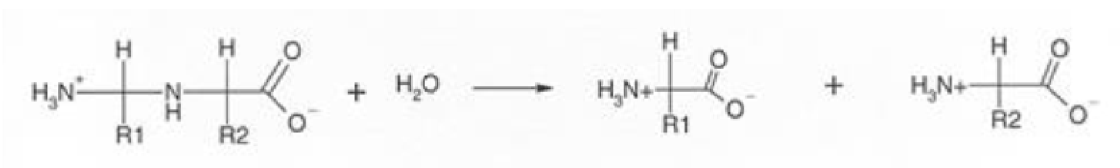

Figure 4 Hydrolysis of Protein
Source: (Rea & Slocum, 2014)

2.4.2 Acidogenesis

Acidogenic bacteria (facultative microbes and obligate anaerobes) degrade the hydrolysed products into volatile fatty acids (VFAs) causing drop of pH. Such VFAs include acetic acid, butyric acid, and others. Other than that, neutral compounds like methanol and ethanol, and ammonia (due to cleavage of protein molecules mainly) are also formed. Also, CO2 and H2 evolve as result of carbohydrates catabolism.

Several reactions takes place in the acid-forming stages, some of them are exemplified below: Eq. 2.1 illustrated the transformation of glucose into ethanol and Eq. 2.2 illustrates the transformation of glucose ($C_6H_{12}O_6$) into an ester i.e. propionate.

$C_6H_{12}O_6 \rightarrow 2 CH3CH2OH + 2CO2$ Eq. 2.1

$C_6H_{12}O_6 + 2H2 \rightarrow 2CH3CH2COOH + 2 H2O$ Eq. 2.2

2.4.3 Acetogenesis

Acetogenesis acts as the third step in the AD process, in which degraded products from beforehand step i.e. acidogenesis are more degraded to produce hydrogen, acetic acid, and carbon dioxide. The microbes (acetogens) function in this phase are mainly hydrogen producing obligate anaerobes. It is a fermentative process with acetic acid as it main product, while by-products depend upon physio-chemical conditions of the environment.

Typical reaction shows the consumption of glucose, given in equation 2.3

$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$ Eq. 2.3

2.4.5 Methanogensis

The final step of AD process is Methanogensis, which involves the formation of methane by bacteria called metagenes. Several simple constituents like methanol (also called methyl alcohol), acetic acid or hydrogen and carbon dioxide (CO2), are responsible for the production of methane. Among these, acetic acid and its salt acetate and acetic acid are responsible for the 75% or one third of the methane being produced in the whole process (Chaudhary, n.d.).

Methanogens i.e. microbes responsible to produce methane, are categorised into two diverse sets; (i) acetoclastic methanogens that consume vinegar or acetic acid (CH_3COOH) mainly, and (ii) hydrogenotrophic methanogens that consume carbon dioxide and hydrogen. Activation of the group in the AD process depends upon the nature and characteristic of raw material. However, acetoclastic methanogens are usually responsible 2/3rd of total methanation formation (Fellowship, n.d.).

$CO2 + 4H2 \rightarrow CH4 + 2H2O$ Eq. 2.4 (hydrogenotrophic methanogens)

$CH3OH + H2 \rightarrow CH4 + H2O$ Eq. 2.5 (acetoclastic methanogens)

2.5 Factors affecting operation of AD process

Parameters affecting the AD process must be controlled and operated in optimum conditions so, to ensure successful completion of the digestions. As, often the case the digestion of solid waste often undergo functional inhibition if, process isn't under effective control. Some of these parameters are discussed below:

2.5.1 Volatile solids (VS)

VS specifies the metabolic standing or activity status of several most sensitive microbes in the AD system. Thus, making VS an important parameter to gauge biodegradation rate of materials present in the AD system. Substances with low biodegradability such as high lignocellulosic organic, straw, sawdust, coarser wood, paper, and cardboard, are either co-digested or are more compatible to waste-to-energy plants. VS being significant parameter, is adequately kept checked and its reduction is measured as per schedule. As it shows the completion of AD process and for the continuous process when addition of feed is continuous it indicates the stability of the process overall. VS can act has an inhibitor if not kept under observation.

2.5.2 Alkalinity and pH

Alkalinity indicates the buffering capacity and preventing rapid change in pH. As, it is referred as to be the capability of neutralizing acid by water. Therefore, it is critical for pH control. As, the proteinaceous wastes are degraded amino groups are released and ammonia is produced which serve as the functional cause of alkalinity. acidic conditions can inhibit or impede the microbial growth logarithm. As, many Anaerobic microbes such as the methanogens, tend to be very sensitive to the change in pH and acid concentration. The pH value of 6.5 to 7.5 is determined to be the optimum value for anaerobic digestion process(Liu & Yuan, 2008). gas production has a significant relation with the pH. It is determined the decrement in pH hinders the biogas productivity as, methanogenesis process is impeded by the build-up of acids.

Throughout the several steps involved in AD process, the pH during Acidogenesis is usually below pH 5 due to production of volatile acids. While, with the progression of the process the pH tends to increase by the formation of ammonia. Mostly, when the pH is low, lime or base is added to adjust the pH to its optimal value. the stability of methane generation, indicates steady pH value level i.e. 7.2 to 8.2. the pH value is stabilized with ammonium concentrations of up to 1000 mg/L, as it acts as a buffer (Chaudhary, n.d.).

2.5.3 Volatile fatty acids concentration

VFA is chief transitional compounds that evolves during the Acidogenesis phase and plays a critical role in methane fermentation. VFA services as controlling function of pH variance in AD process, therefore, if present in high concentrations, can cause microbial stress. VFAs such as; acetic acid (CH_3COOH), valeric acid, butyric acid, and propionic acid evolve through anaerobic bio-degradation of organic substances (Chaudhary, n.d.).

Some of the important parameters with their inhibitory concentration for AD are exhibited in Table 1:

Table 1: Inhibitors of biomethanization

Parameter	Inhibiting concentration (mg/L)
Volatile acids	>2,000 (as acetic acid) 6,000-8,000 (tolerate)
Ammonia nitrogen	1,500-3,000 (at pH>7.6)
Sulfide (soluble)	>200; >3,000 toxic
Heavy metals Copper (Cu) Cadmium (Cd) Iron (Fe) Chromium (Cr+6) Chromium (Cr+6)	0.5 (soluble metal) 150 Millimole of metal per kg of dry solid 1710 Millimole of metal per kg of dry solid 3 500 2
Calcium	2,500-4,500; 8,000 (strongly inhibitory)
Magnesium	1,000-1,500; 3,000 (strongly inhibitory)
Potassium	2,500-4,500; 12,000 (strongly inhibitory)
Sodium	3,500-5,500; 8,000 (strongly inhibitory)

Source: (Poprasert, 1996)

VFA concentration in AD process varies throughout such that, often, during start-up of dry anaerobic digestion, VFA accumulation happens. It happens because during start up readily degradable substances are more stepped into acidogenesis phase and buffer capacity is not attained as end products of other phases are not in equilibrium yet. Similarly, loading the reactor beyond its working or handling capacity also leads to VFA accumulation. However, presence of proteins or of ammonia is higher concentrations then, build-up of VFA will not cause acidification. As, proteins contain nitrogen that end up emanating ammonia and ammonia itself acts as a buffer (Fellowship, n.d.)

2.5.4 Temperature

Successful completion of an AD process largely depends upon the temperature conditions prevailing with in the digester. As, microbial population dynamic is function of temperature as well. Therefore, there are two temperature ranges for optimal operation of the digester i.e. the mesophilic (30°C - 35°C) and as for thermophilic range is (50°C-65°C) (Bouallagui et al., 2004). Although, thermophilic temperature conditions reduce the required retention time, but are subtler to toxins and minor changes in the environment due to short mass retention times (MRT).

2.5.5 C/N ratio

The C/N demonstrates the proportion of carbon (C) and nitrogen (N) in any organic substance. Microbial population dynamic is affected by C/N as, they need nitrogen to produce new cells. An optimum ratio of nutrient for mechanisation is P:S:C:N =5:3: 600:15. For the adequate degradation of carbon constituted in the organic waste, sufficient level or quantity of nitrogen should be present in the overall feed + inoculum mixture. Therefore Optimum 20-30 ratios of C/N should be maintained (Fellowship, n.d.).

In the process of AD, the reduced nitrogen compounds are not removed. Thus, implying that an adequate proportion between Carbon and Nitrogen in the feed is critical. A high C/N ratio lets the methanogens to consume nitrogen quickly thus, results lower gas productivity. In contrary, a lower C/N ratio i.e. higher nitrogen or low carbon content, causes ammonia accumulation which can cause inhibition. Also, increment in pH value is observed when C/N ratio is high such that it exceeds pH of 8.5. As, higher pH is noxious to methanogens, it impede the AD process (Yenigün & Demirel, 2013). Substances with high C/N rations can be mixed with that of low C/N ratios or co digested to achieve optimum C/N proportion, such as OFMSW co-digested with sewage, paper, or animal manure.

Table 2: Typical C/N ratio for various materials

Raw material	C/N Ratio
Duck Dung	8
Human excreta	8
Chicken Dung	10
Goat Dung	12
Pig Dung	18
Sheep Dung	19
Cow Dung	24
Water Hyacinth	25
Municipal Solid Waste	*40*
Elephant Dung	43
Maize Straw	60
Rice Straw	70
Wheat Straw	90
Saw Dust	>200

Source: (Bouallagui et al., 2004), (Liu & Yuan, 2008), and (Yabu et al., 2011)

2.5.6 Organic Loading Rate (OLR)

OLR signifies the performance of the AD system as, it is gauges the conversion capacity of microbes. OLR signifies the availability of nutrient in the material. Therefor if, the digester is fed with OLR above the optimum and sustainable rate it will yield low biogas because accumulation of any substance beyond its optimum level serves as a toxic for the microbes. Thus, Organic Loading Rate is a critical control factor in semi continuous and continuous systems as, it may cause the failure of the system. The quantity of substrate a digester can process while assuring efficient process performance is given by Eq. 2.6

$$OLR = \frac{Q*S}{V} = \frac{S}{R*T} \quad \text{Eq. 2.6}$$

here

OLR = organic loading rate (kg substrate/m3 digester)

S = concentration of substrate (kg substrate in terms of TVS)

2.5.7 Mixing

Contact between active bacteria and the slurry is critical to the AD system performance. Therefore, this contact should be maintained at sufficient rate by mixing either manual or mechanical. As, mixing not only allows enhanced contact between the material and microbes, but also prevents deposition of dense particles at the bottom of the digester and assists the outflow of generated biogas. Further, mixing enables homogenous heat transfer and preventing the launch of temperature gradients in the digester (Fellowship, n.d.).. When microbes are inoculated inside digester, they show similar behaviour as they do in the stomach and gut of the animals. They rather than being in motion with in digester slurry, adhere to the walls and surfaces available in the digester (Rea & Slocum, 2014). To address this issue, either internal structures are designed within the digester or mixing is done to achieve efficient digester performance.

Several methods and procedures can be opted for mixing. Such as, mechanical or manual mixers, recirculation of the produced biogas or Digestate. Also, the energy required for mixing is the function of solid concentration, characteristics of waste, volume, and the mechanics of the equipment (Stafford, 1981). However, among all the mixing techniques digestate recirculation is by far the best option (Karim, Hoffmann, Klasson, & Al-dahhan, 2005). Along with method, mixing could be continuous or intermittent. however, (Stafford, 1981) suggested that intermittent mixing is most suitable for higher biogas production.

2.6 Dry Anaerobic Digestion Optimization Techniques

To improve AD process, pre-treatment of waste is considered an efficient option. The pre-treatment may involve the removal of the nonbiodegradable materials, effective average particle size, and screening or elimination of substances with potential to impair or cause physical damage to digester or decrease the quality of the digestate. Similarly, chemical and thermal pre-treatments can decrease retention time by improving solubilisation and hydrolysis (Fellowship, n.d.).

Min categories of pre-treatments for dry AD are:

- Physical pre-treatment

• Chemical pre-treatment

• Biological pre-treatment i.e. use of inoculum

2.6.1 Physical Pre-treatment

To have a resourceful AD operating system, the interfering impurities such as glass, plastics, metals, stones, and others must be eliminated by waste separation. It can be either source separation or mechanical separation. Mechanical separation is done often when waste isn't source separated at all or is inadequate. Such methods involve screening and shredding. Non-digestible particles or pollutants that exceeds the average size of 40 mm are removed by the Screening process. While, shredding is most opted method as it reduces particles along with exposing microbes to the greater surface area (Izumi et al., 2010). Thus, speeding up the digestion of the waste.

2.6.2 Chemical Pre-treatment

It mainly involves alkaline treatment i.e. addition of Alkalis. It increases the pH to 8-11. Furthermore, soluble substances such as carbohydrates, proteins, lipids, or lower MW substances are also attained after the degradation of larger or complex particulate OM. Thus, waste composition is changed and the overall digestion process is accelerated.

2.6.3 Biological Pre-treatment (inoculation)

The AD involves consortiums of inter-reliant microbes for the decomposition of complex OM. Therefore, it is an intricate biological process. Thus, it is not adequate to estimate the generation of methane merely by substrate characteristics and its chemical composition . Also, a balanced active inoculum ratio is critical for the effective performance of the AD system (Vrieze et al., 2015).

Inoculum needs to be added in an adequate proportion i.e. S/I ratio (substrate – inoculum). S/I ratio is the percentage of inoculums in substrate on volatile solids basis. Inoculum reduces the time required for acclimation by microbes thus, omitting the lag phase of their growth logarithm and accelerating the start-up of digester. Therefore, several materials can efficiently be used as an inoculum source such as anaerobic sludge, ruminant manure, etc. Vrieze and Raposo have concluded that for dry AD, the optimum Substrate to inoculum ratio is 1.0 or less than 1 (Vrieze et al., 2015) and (Raposo et al., 2009).

3 Methodology

3.1 Introduction

In this research, a pilot scale hand driven energy efficient anaerobic digester was designed to observe and optimize functional parameters such as OLR, temperature, retention time etc. for the effective operation of AD system. Food waste was used as substrate, which was collected from cafeterias and hostels' mess of NUST campus. The collected waste was manually sorted to remove unwanted materials such as plastics or bones from readily biodegradable organic fractions of waste. The segregated waste was then shredded with a meat grinder to an average size of 10mm. It was then thoroughly mixed with inoculums that provided the required microbial consortia to enhance the digestion process. Inoculums used were cow dung and slurry. mesophilic condition of 37◦C was maintained during the operation of the reactor . For this purpose, a water jacket and temperature controller system were installed with the digester.

3.2 Pilot scale semi - continuous digestion system

3.2.1 Digester Design

The digester was design as per the optimum OLR and HRT. A double walled digester in cylindrical in shape was designed. The double wall of the container was to circulate hot water to maintain the temperature inside the reactor. At the rear bottom the double was extended to shape it into closed water bath. The reactor was also facilitated with piped outlet at its rear to ensure adequate digestate disposal. This disposal outlet doesn't let the of air to intrude into the reactor while withdrawing digestate or slurry. Thus, maintaining the anaerobic conditions within. A bucket was used to collect the withdrew digestate and part of it was recirculated in the later days.

The digester was designed having capacity of 100 L with 20-25L spared for the biogas accumulation and rest of 75-80 L as the working volume . The reactor was designed with the inside diameter of 40cm. The reactor was also facilitated with necessary equipment such as heater (immersion heating rod), temperature controller, and wet gas meter. The mesophilic condition (37C) within the digester were maintained by utilizing heater to heat water bath. The temperature controller simultaneously controls the functionality to the heater and did not let it heat beyond the set the temperature. Wet gas meter uses water bubble concept to gauge biogas production. One count of wet gas meter was considered equal to 18mL of biogas

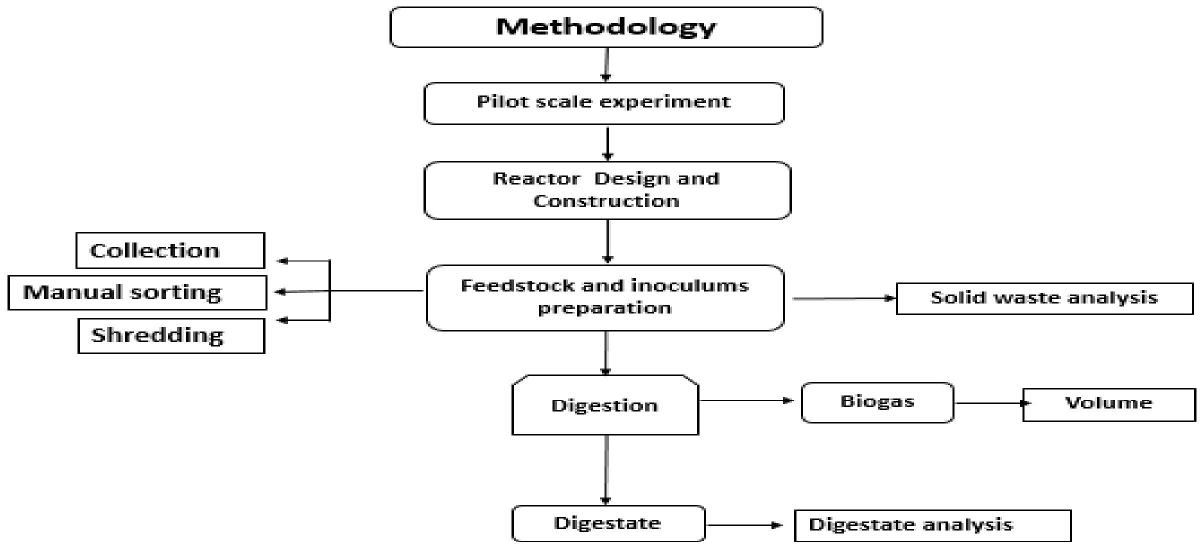

Figure 5 Diagram of project methodology

3.2.2 Experimental procedure

a. Feedstock preparation

Food waste form NUST hostels, cafeterias, and Sabzi Mendi of I9 was collected. Due to the presence of several undesired materials such as plastic, product packages, etc. manual sorting was done. food waste contained vegetables and fruit wastes, orange pulp, shredded chicken, and boiled rice to appropriate proportion. After manual sorting shredding was done to reduce particle size upto 10mm, using manual meat shredder. Shredding increases the surface area which accelerate the hydrolysis process and the methanogenesis process. For the startup process, collected food wastes was mixed with the inoculums. Inoculum provide microbe diversity thus, accelerating digestion process.

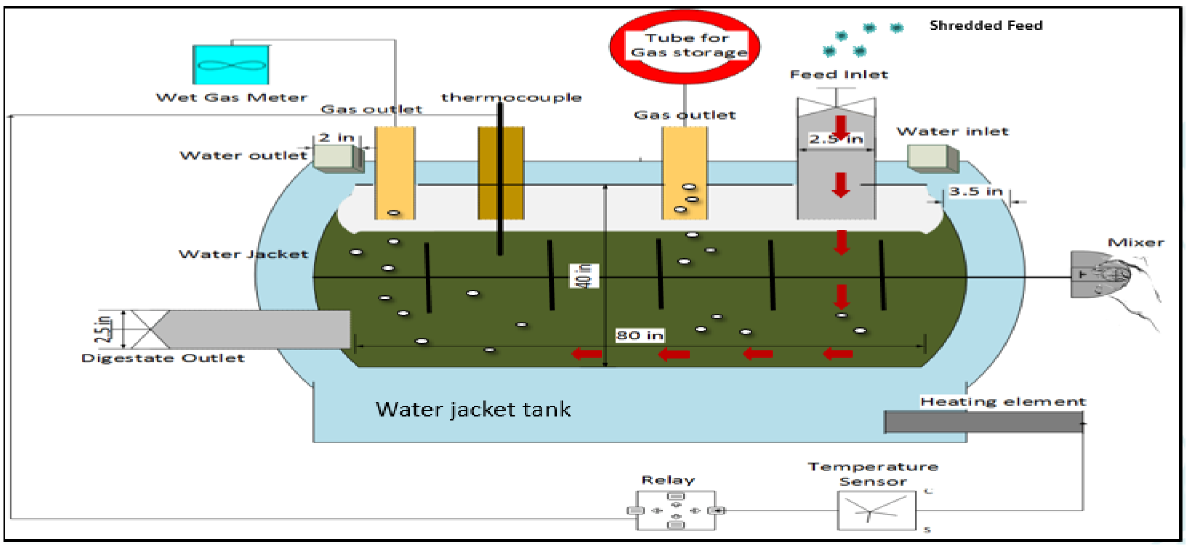

Figure 6 pilot scale dry anaerobic digestion system design

b. Inoculums

The AD involves consortiums of inter-reliant microbes for the decomposition of complex OM. Therefore, it is an intricate biological process. So, a balanced active inoculum ratio is critical for the effective performance of the AD system (Vrieze et al., 2015). 80% of the digester volume filled with substrate (70% w/w) and inoculum (30% w/w) i.e. 80L. Carreiro reported that 30% (w/w) of inoculum mixed in organic wastes feed is optimum for acidogenic fermentation (Carreiro et al., 2006). Cow dung and slurry was used as inoculums components. cow dung and slurry were mixed in the proportion of 1:1 to prepare effective inoculation seed or inoculum for the digester.

c. Digester operation procedure

The working volume i.e. 80% of the digester volume filled with substrate (70% w/w) and inoculum (30% w/w) i.e. 80L. The pH of the digester was adjusted by the addition of sodium bicarbonate and sodium hydroxide. The single stage pilot scale reactor operated under dry AD system i.e. solid content > 15%. Throughout the operation phase frequent analysis of digestate was ensured. So, to maintain the operating conditions and to check the completion of the startup phase. Also, the feed and the digestate sample were tested as per schedule (see Appendix E) to observe the values and trend of parameters with inhibition potential such as Volatile Fatty Acids, pH, and ammonia nitrogen. Once the startup phase is completed, continuously feeding can be done per the designed loading rates.

After 15-20 days of startup, the digestate was withdrawn daily and part of it was recirculated into the digester. Recirculation of the digestate enhances the mixing and ensure homogenized conditions within the digester. Biogas produced was monitored daily.

3.3 Sampling and analytical procedure

Throughout the project scheduled testing of feedstock and digestate was done. In this regard, parameters like MC, Ammonia, VFA, pH, Total Solids, and Volatile solids were analysed. Careful observation of these parameters' trends was ensured to keep the system stability and performances in check. All analytical determinations were performed per "Standard Methods"(American Public Health Association, AWWA (American Water Works Association), n.d.). In addition, nutrients analysis i.e. nitrogen and carbon of the fresh wastes, and digestate was also done.

3.3.1 Solid waste analysis

The analysis involved scheduled testing of fresh and digested waste. grab samples were collected for the analysis and were handled according to the standard procedures. The parameters under analysis were MC, Total Solids, Volatile Solids, Ammonia, and bulk density.

- **Moisture content**

Moisture Content (MC) is the percent of moisture or water content present in the sample. To determine MC a sample of 100 g was collected and kept in the pre-weighed dish in the oven for drying at 105 ^{o}C for 24 hours to a constant weight. After 24 hours dried sample were weighed. Eq. 3.6 and 3.7 were used to calculate the percent MC and TS. Subsequently, the samples used to determine MC were then utilized to determine the VS.

% MC = [(Wet Weight – Dry Weight)/ Wet Weight] x 100%	Eq. 3.6
%TS = 100% - %MC	Eq. 3.7

- **Volatile solid**

the method of ignition was used to determine the volatile solid content of the fresh waste and digestate samples. In this regard, the sample was kept in muffle furnace at 550°C for 1 hour. Before the sample to be placed in a muffle furnace, it had to be oven dried. Therefore, the very same sample used to determine moisture content and total solid was used determine volatile solids. The oven dried samples were pulverized and mixed appropriately to ensure homogeneity. Once pulverized, the sample were weighed and place in muffle furnace for at least 1 hour at 550^{o}C. After drying of 1 hour the samples were then cooled down in a desiccator. Subsequently, weighing of the cooled samples was done. Eq. 3.8 was used to calculate the volatile solid.

$$\% \ VS = \frac{w0 - wf}{w0 - we} \ x100\% \qquad \text{Eq.3.8}$$

Here w_0 = weight of sample with evaporating dish after 105^{o}C

w_f = weight of sample with evaporating dish after 550^{o}C

w_e = weight of empty dish

Results and Discussions

4.1 Introduction

The following section explains the results obtained through operation of pilot scale anaerobic digester in mesophilic condition. Experiments were conducted for the startup phase of the reactor. The feedstock characteristics are presented and analysis of parameters affecting the performance of the reactor is described in this section. All the parameters tested during the study were analysed using standard methods.

4.2 Feedstock Preparation

In this study, the substrate used was food waste collected from student cafeterias and hostel mess. The waste was stored in refrigerators at 4◦C until the total required amount was collected. Prior to loading of the reactor, the waste was shredded to an average size of 10mm with the help of a meat grinder and thoroughly mixed with inoculum. Cow dung and slurry were used as inoculums which were obtained from a nearby dairy farm.

4.3 Feedstock Analysis

Samples of substrate, inoculum and their mixture were taken in plastic bags, dried in oven and analyzed for moisture content, total solids, total volatile solids and total organic carbon. These parameters were analyzed using standard methods. The feedstock comprised of mixture of cooked waste, vegetable waste and fruit waste to obtain the desired C/N ratio. Its characteristics are presented in the table 3

Table 3: Feedstock Characteristics

Parameters (%)	**Food Waste**	**Slurry**	**Cow Dung**	**Substrate +Inoculum**
Moisture Content	78.37	91.17	80.8	80.52
Total Solids	21.61	8.83	19.7	19.48
Volatile Solids	78.7	61.6	61.4	64.7
Total Organic Carbon	45.65	35.73	35.62	37.53

The table shows that the moisture content of food waste is quite high due to the presence of vegetables and fruit peels. For dry anaerobic digestion process, total solids in the feed material should be greater than 15%. As the total solids content in substrate and inoculum mixture came out to be 19.48%, it was suitable for dry anaerobic digestion.

4.4 Reactor start-up

The total volume of the reactor was 100L. It was filled to 80% of its volume i.e. 80L with feed material with 70% of it comprising of food waste and 30% of inoculums. Through measurement of densities of substrate and inoculums, their equivalent weights to be added to reactor were calculated. The total weight of waste fed including inoculums was 76kg with 54kg of it being food waste and 22kg of cow dung and slurry. The ratio of these inoculums was 1:1. The composition of feed material added to reactor is presented in table 4

Table 4: Feedstock Composition

Substrate 70% (w/w)	**Inoculum 30% (w/w)**
Cooked waste = 40.93%	Cow dung = 50%
Fruit waste = 19.63%	Digested Slurry= 50%
Vegetable waste = 39.45%	

The reactor was operated for 90 days in batch mode. It was provided with mesophilic conditions by maintaining its temperature at 37◦C. To homogenize and enhance the biodegradability of the feed, mixing was done through recirculation of waste and mixer of the reactor.

4.5 Biogas generation

Figure 7 represents the daily and cumulative biogas production. At the initial phase of the digestion process, biogas production was low due to the decrease in pH resulting from formation of volatile fatty acids. These acids produced by acidogens at initial phase of digestion hinder the growth of methanogenic bacteria, thereby inhibiting biogas production (Adedipe, Sridhar, & Verma, 2005). As the startup reached Methanogensis, biogas production started where it was high in the beginning owing to confined air inside and formation of carbon dioxide in large amount. This was due to the addition of sodium bicarbonate and sodium hydroxide to increase the pH which led carbon dioxide to be evolved. The highest volume of biogas produced was 37.07L. After achieving it highest value, biogas production rate fell and became constant. This was due to the exhaustion of substrate available for microorganisms for degradation and biogas production. The total cumulative biogas produced during the startup was 135L.

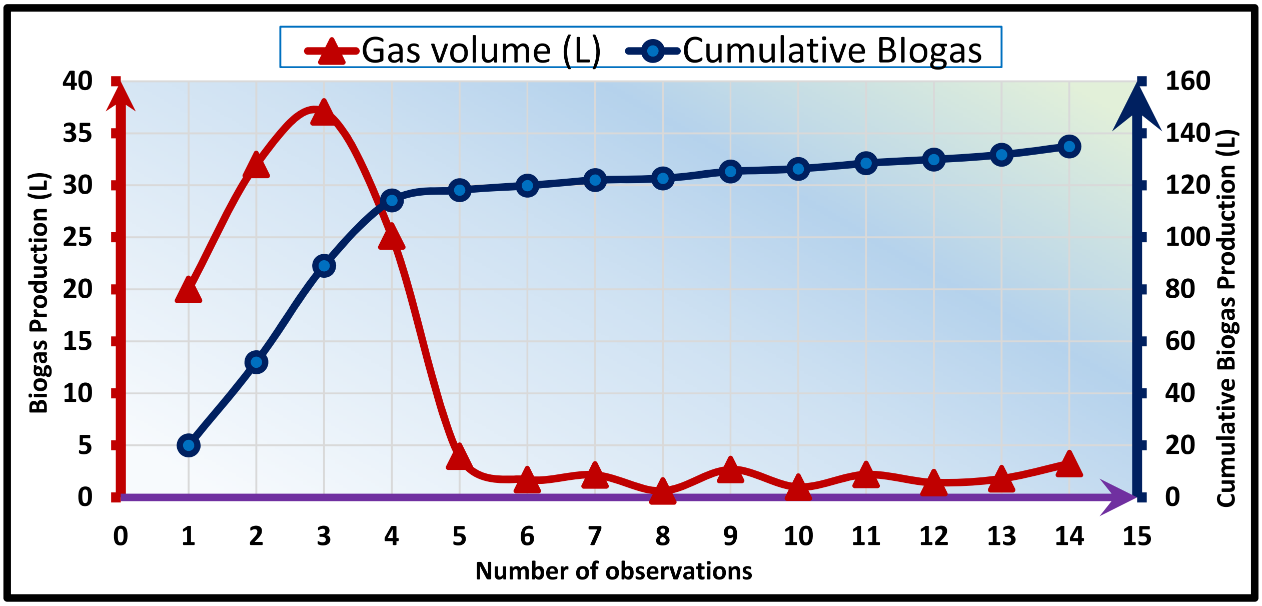

Figure 7: Daily and cumulative biogas production

4.6 Digestate Analysis

4.6.1 Alkalinity and pH

Figure 8 shows the trend of pH and alkalinity of digestate during the startup phase. During the first 10 days, pHwas low in the range of 4-6 due to acidogenesis process of digestion. The VFA generation rate was higher than its rate of degradation into biogas, which led to an accumulation of VFA in the system and hence decreasing the pH (Liu & Yuan, 2008). The alkalinity was zero during this phase. pH was adjusted to its optimum value of 6.5-7.5 by addition of sodium bicarbonate and sodium hydroxide. This also led to an increase in alkalinity due to increment in carbonates concentration. From day 20 to 40, pH and alkalinity remained stable but no biogas production started due to lack of proper mixing. Therefore, recirculation of waste was done from day 46 which led to an increase in PH and alkalinity. The pH reached above 7.5 but then exceeded 8.5 which are inhibiting conditions for methanogenesis. Hence it was brought back to its optimum range of 6.5-7.5 by adding sulfuric acid. As the rate of methane production started to increase, the pH then stabilized and stayed constant till the end of the AD process. This was due to the buffering capacity of the system and conversion of volatile fatty acids into methane and Carbon dioxide.

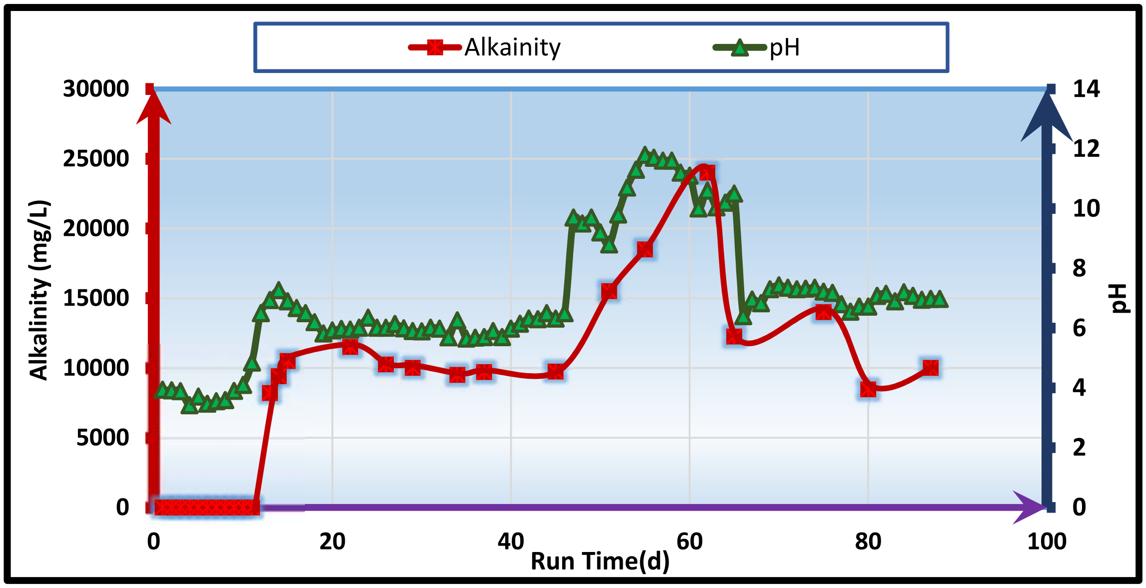

Figure 8: pH and alkalinity of digestate

4.6.2 Volatile Fatty Acids

Figure 9 shows the variation in concentration of volatile fatty acids during the startup period. VFA production was high in the initial phase due to acidogenesis and acetogenesis. During these two phases, the acid forming bacteria convert the monomers formed by hydrolysis phase into short chain organic acids which are then converted to acetic acid, carbon dioxide and hydrogen by acetogens (Karim et al., 2005). The VFA generation dropped from day 15 to 78 and was below its inhibition limit of 6000 mg/L. pH was also found to be in its optimum range of 6.5-8. During this phase methanogenesis was dominant during which acetic acid, carbon dioxide and hydrogen; formed from earlier stages were converted to methane and carbon dioxide (Liu & Yuan, 2008). After day 80, a rise in VFA concentration can be seen which is due additional feeding of the reactor with food waste.

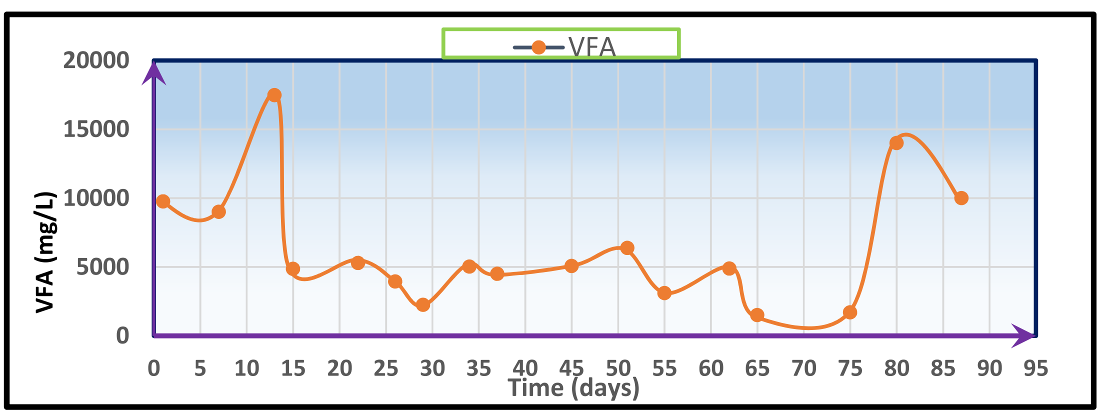

Figure 9: Trend of VFA concentration

4.6.3 Total Ammonia Nitrogen

Figure 4.4 shows the variation in concentration of Total Ammonia Nitrogen. In this study, its value was within the range of 200-1400mg/L. The optimum range of TAN for AD process is below 3000 mg/L (Yenigün & Demirel, 2013). Since the value of TAN remained within its optimum range throughout the AD process, we can infer that ammonia inhibition did not occur.

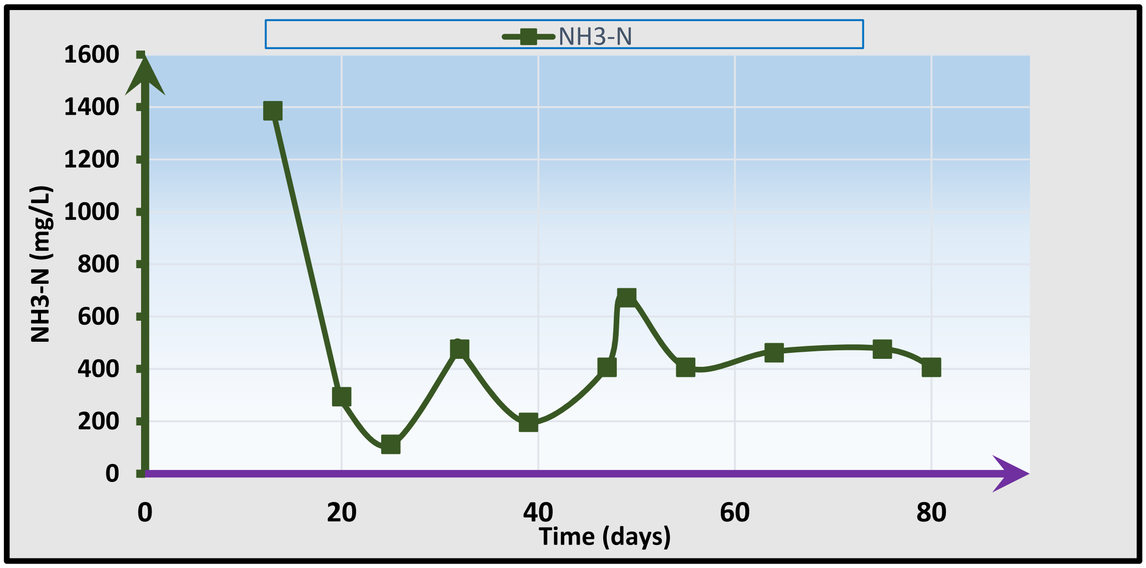

Figure 10: variation in concentration of Total Ammonia Nitrogen

4.6.4 Total solids and Volatile solids

A general decrease was observed in the total solids content with time due to degradation of substrate by microorganisms inside the digester. Similarly, volatile solids content was also reduced due to their consumption and conversion into biogas. (Uzodinma, 2015) reported that during anaerobic digestion, degradation caused by microorganisms would reduce the net available quantity of TS and VS of organic wastes.

4.7 Conceptual framework for NUST anaerobic digestion plant

In this section, an anaerobic digestion plant is proposed for NUST for treating its organic fraction of solid waste which is currently disposed of in a landfill.

The analysis of design, operating system, energy potential of AD plant and its greenhouse reduction potential are also elaborated in this section. According to waste management data collected from NUST Admin Office, the daily amount of the solid wastes generation in NUST is about 28000 kg/d which comprises of 60% organic wastes and are well suitable feedstock for the anaerobic treatment technology.

4.7.1 Design of AD treatment plant

Experimental results show thatthe required volume of the reactor should be be $56m^3$ which can be designed to treat the current amount of NUST solid wastes (Appendix C). Pretreatment facilities will be installed with anaerobic digestion plant for the arriving organic waste before inserting it into the system. The pretratment process will mainly comprise of shredding and pumping of organic waste provided the feedstock is source segregated. After the treatment inside thereactor, dewatering of the sludge can be done through sludge drying method. The dried sludge can be further used as fertilizer.

4.7.2 Operation of the system

The process of feeding and residual removal will be done every day. The retention time of the reactor will be be 25 days. The waste will undergo the pretreatment processing before being loaded into the reactor to ensure proper operation of the system.. Daily monitoring of biogas composition and pH of the digestate will be done to prevent any disturbance in reactor operation. As storage of biogas for a longer period is difficult, the system should be equipped with a conversion facility that can convert biogas into electrical energy.

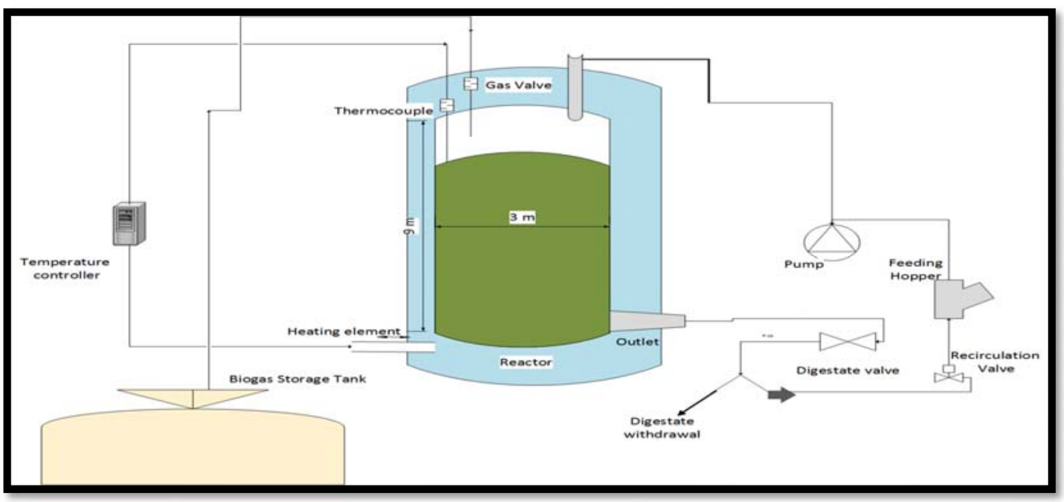

Figure 11: AD plant for NUST

4.7.3 Energy Potential

The amount of biogas produced from the proposed plant will be sufficient in supplying electrical energy for the operation of the system itself as well as theNUST community. The daily amount of the surplus energy produced from this system will be **2678.33 MJ** (Appendix C).

4.7.4 Mitigation of greenhouse gases emissions

The energy conversion can play a vital role in reducing carbondioxide and methane composition of green house gases from atmosphere.. The waste sector can be easily managed and requires less effort as compared to other energy sectors in regard to decreasing greenhouse effects(Dhaka, 1994). The reductions of the methane after introducing this biological treatment plant will reduce **4.09 ton CO2-eq/day** of CH4 (Appendix C). So, this system has the significant effect on the reduction of greenhouse gases and preventing the unusual climate change.

5 Conclusions and Recommendations

5.1 Conclusions:

Food waste constitutes the major organic fraction of Municipal Solid Waste that goes into the landfill where it is responsible for the generation of high amount of methane. Reducing the quantity of food waste from landfill can contribute significantly towards climate change mitigation and environmental pollution reduction. Moreover, it can be treated and used as a source of renewable energy through the process of anaerobic digestion. This technology generates two valuable products: biogas and digestate that may be utilized as fuel and soil fertilizer respectively. Food waste has higher biogas potential then other sources like agriculture and wastewater sludge.

In view of this, an eco-friendly, energy efficient and easily operated anaerobic digester was designed to extract energy from food waste. The designed reactor was of 100L volume and made up of stainless steel. It related to a temperature controller system to maintain its mesophilic temperature. The reactor was operated in batch mode and its performance was analyzed throughout its operation.

56 kg of food waste collected from hostel cafeterias and hostel mess of NUST campus was co digested with 22kg cow dung and slurry combined. Prior to mixing, shredding of food waste is an essential step for efficient digestion. For this purpose, a meat grinder was used to shred the waste to an average size of 10mm. Another important aspect of anaerobic digestion is proper mixing of the substrate and inoculum to provide homogenized conditions inside the digester. Hence intermittent mixing was ensured with the help of a manual mixer installed inside the digester. Intermittent mixing has been shown to give similar results of biogas production as continuous mixing but with the option to reduce the maintenance and energy requirements of the process.

The results of the study show that anaerobic digestion is an efficient method to treat the organic fraction of food waste. The system was successful in terms of reduction of waste volume and organic load. The biogas production capacity of the digester was also good once all performance parameters achieved their optimum conditions. However, addition of an alkali was essential to stabilize the pH during reactor startup.

The design of digester is one of the aspects that need attention. It can be improved through installation of a more efficient design of mixer and inlet of digester that would enhance its usability.

Moreover, maintenance services are also needed to ensure long-term and sustainable use of the system. The co- digestion of food waste and fresh cow dung proved to be suitable with feed size of 10mm. The process was successfully demonstrated by using temperature controlled system to maintain mesophilic conditions in batch mode. The resulting successful production of biogas was used for heating purpose such as boiling of water.

5.2 Recommendations:

- Implementation of source segregation of organic fraction of Municipal Solid Waste and its treatment through proposed anaerobic digestion plant for NUST is a viable option for sustainable solid waste management and energy production.
- Blending of different fractions of the organic wastes is necessary to achieve the optimum C/N ratio.
- Co digestion of food waste with cow dung aids in stabilization of unsteady conditions during the initial phase of reactor startup
- Intermittent mixing of feed inside the digester is sufficient during the batch mode
- PH needs to be stabilized during the startup phase of the reactor with addition of an alkali
- As the methane is one of the major contributors of greenhouse effect, it should be captured and made to use or disposed of properly.
- A two-stage operated AD system can provide better process control and higher methane yield
- The distance of pipelines between digester and gas storage tank should be minimum to avoid biogas leakages

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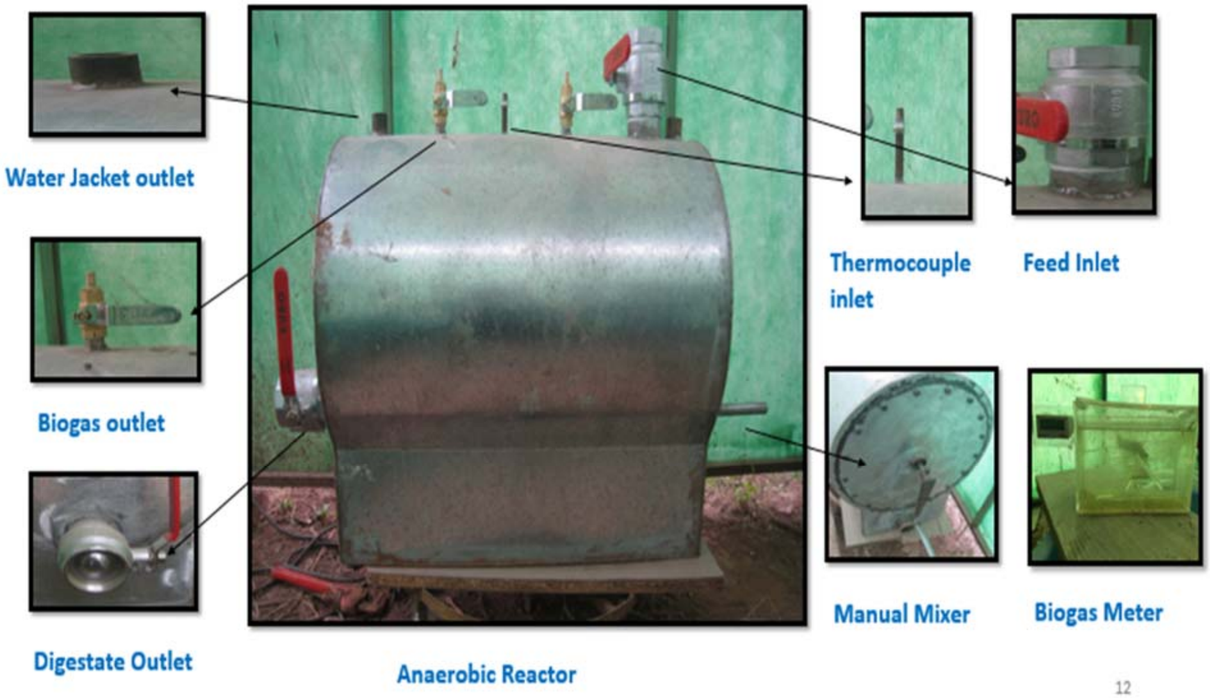
Appendices



Appendix A: Photograph

Appendix B: Sample calculation

1. Moisture content and Total Solid (TS)

Weight of sample before drying = 85.28 g

Weight of sample after drying = 10.57g

$\% \text{ MC} = \frac{(85.28 \text{ g} - 10.57\text{g})}{85.28} \times 100 = 87.61 \%$

% TS = 100 – 87.61 = 12.39 %

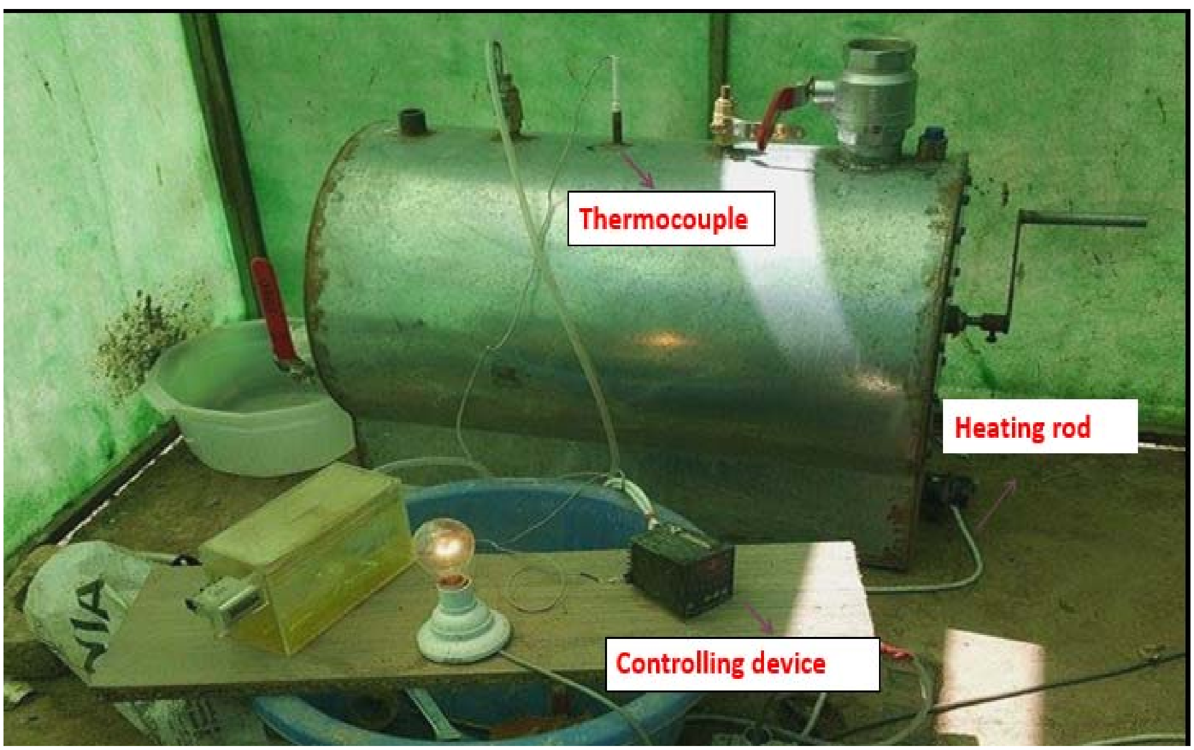
2. Volatile Solids (VS)

Weight of sample after 105 $_o$C = 58.98 g

Weight of sample after 550 $_o$C = 47.15 g

$\% \text{ VS} = \frac{(58.98 - 47.15)}{58.98} \times 100 = 83.54 \%$

Total Wet Weight (WW) of sample = 48 kg



Dry Weight (DW) = (WW X % TS) = 48 kg x .1239 = 5.94 kg

Volatile Weight = (DW X % VS) = 5.94 kg x 0.8354 = 4.968 kg

3. Total Organic Carbon (TOC)

TOC = %VS / 1.724

TOC = 83.54 / 1.724 = 48.56

Appendix C: Calculation of Proposed Decentralized AD Plant

Assumptions

Total waste generated by the community: 2.72 t/d (Source: NUST Administration)

Weight of organic waste: 60 % of total waste = 0.60 x 2.72 = 1.632 t/d,

TS of waste: 18 % = .18 * 2.72t/d = 293.76 kg

VS of waste: 84 %TS = .84 * 293.76 = 246.76 kg VS/d

Density of pre-treated waste: 1029 kg/m^3 (Lab test)

Reactor working volume: 75 % of total volume

1. **Calculations for volume of reactor**

   Method 1:

   $$\text{Working volume of reactor} = \frac{\text{VS (kg) to be added per day}}{\text{VS load (kg VS/m}^3\text{.d)}}$$

   $$\text{Working volume of reactor} = \frac{246.76 \text{ kg VS/d}}{6} = 41.13 \text{ m}^3$$

   Reactor total volume: 41.13 x 100/75 = **54.84 m^3**

Method 2:

VS to be added per day = 246.76 kg VS/d

Volume of organic waste = weight/density = 1632 (kg/d) / 1029 kg/m3 = 1.586 m3/d

Working volume of reactor (L) = Flow rate (L/d) * RT (d)

= 1586 x 24 = 38064 L = 38.06m3

OLR at this volume = 246.76 (kg VS/d)/ 38.06 m3 = 6.48 kg VS/ m3.d

Working volume of reactor at OLR of 7.0 kg VS/m3.d = 48 x 6.48/7 = **44.43 m3**

Total volume: 44.43 x 100/75 = **59.25 m3**

Considering working volume of 59.25 m3 to be final volume

Considering cylindrical shaped reactor or AD digester

Dimension of digester = $\pi * r^2 * h$

$= 3.14 * (1.5\ m)^2$ (radius) * 8.5 m (height) = 60.05 m^3

Daily amount of waste to feed: 1632 kg/d

2. **Calculation for methane or biogas yield**

Specific methane production = 300 L/kg VS (Chaudhary, n.d.)

Methane production = volatile solids x specific methane production

Organic fraction of NUST waste is 1632 kg, having 246.76 kg VS/day

So, Methane Yield of NUST AD Plant is:

= 246.76 (kg VS/d) x 300 (L/kg VS)

= **74.028 m3 CH4/day**

3. **Energy and electricity generation**

The energy production EP (MJ) is equivalent to methane and hydrogen content of the produced biogas

EP = (MP X L.H.V. of CH4)

where

MP = methane production (L CH4)

L.H.V. of CH4= 0.03618 MJ/L CH_4 (Ruggeri et al., 2010)

therefore, energy of **2678.33 MJ or 2.6784 GJ/d** can be achieved, which can produce electric energy of **10.23 kW**

4. **Calculation of GHG emission reduction**

Landfill methane production = 140 L/kg waste (Bogner and Spokas, 1993)

Total methane emission, if the community landfills all the waste,

= 1632 kg waste /d 140 *L CH_4/kg waste = 228480 L CH4 = 282.48 m3 CH4/d

= 282.48 m3/d x 0.000717 tons/m3 (Density of methane)

= 0.164 tons CH4/d = 0.2 (ton CH4/d) x 25 (tons CO2-eq/ton CH4)

= 4.09 ton CO2-eq/day

Appendix D Pilot scale anaerobic digestion Experiment

Table 5: Operational Parameters of Anaerobic Digestion During Pilot Experiment

Run Time (days)	pH	VFA (mg/L)	Alkainity (mg/L)	NH3 (mg/L)	TS (%)	VS (%)	M.C (%)	TOC
1	3.94	9750	0		12.39	83.54	87.61	48.46
2	3.92		0		11.77	82.73	88.23	47.99
3	3.89		0		7.81	78.92	92.19	45.78
4	3.42		0		10.06	79.86	89.94	46.32
5	3.71		0		11.32	89.57	88.68	51.95
6	3.47		0		10.93	80.59	89.07	46.75
7	3.55	9000	0		12.11	82.14	87.89	47.65
8	3.59		0		12.85	84.63	87.15	49.09
9	3.9		0		13.40	92.90	86.60	53.89
10	4.1		0		13.00	89.95	87.00	52.18
11	4.85		0		12.90	92.04	87.10	53.38
12	6.5				12.66	90.00	87.34	50.66

13	6.94	17475	8200	1386	9.08	79.21	90.92	45.95
14	7.27		9412		9.28	78.88	90.72	45.75
15	6.9	4860	10500		9.52	75.39	90.48	43.73
16	6.67				10.69	77.44	89.31	44.92
17	6.5				15.00	78.09	85.00	45.30
18	6.2				11.84	81.98	88.16	47.55
19	5.82				13.90	70.46	86.10	40.87
20	5.92			294	13.14	72.00	86.86	
21	5.97				12.22	75.25	87.78	43.65
22	5.95	5287	11500		11.56	77.30	88.44	
23	6.01				14.75	94.08	85.25	54.57
24	6.35				15.00	89.50	85.00	
25	6.01			112	11.84	81.98	88.16	47.55
26	6.01	3937.5	10250		13.90	78.46	86.10	45.51
27	6.14				11.50	76.20	88.50	
28	5.99				12.22	75.25	87.78	77.97
29	5.9	2250	10000					
30	5.89							
31	6.01							
32	5.98			476				
33	5.69							
34	6.26	5025	9500					
35	5.65							
36	5.68							
37	5.7	4500	9700					
38	5.9							
39	5.7			196				
40	5.98							
41	6.15							
42	6.32							
43	6.3							
44	6.5							
45	6.32	5062.5	9750					
46	6.5							
47	9.7			406				

48	9.5							
49	9.7			672				
50	9.2							
51	8.8	6375	15500					
52	9.8							
53	10.7							
54	11.3							
55	11.8	3100	18500	406				
56	11.7							
57	11.6							
58	11.6							
59	11.2							
60	11.1							
61	10							
62	10.6	4875	24000					
63	10.04							
64	10.2			462				
65	10.5	1500	12250					
66	6.4							
67	6.96							
68	6.83							
69	7.3							
70	7.43							
71	7.35							
72	7.3							
73	7.32							
74	7.35							
75	7.22	1700	14000	476				
76	7.18							
77	6.8							
78	6.55							
79	6.72							
80	6.72	14000	8461	406				
81	7.08							
82	7.15							

83	6.9							
84	7.2							
85	7.08							
86	6.95							
87	6.98	10000	10000					
88	6.98							

Appendix E Solid waste characteristics of fresh waste

Table 6: Fresh feed and inoculum constituents

Substrate	Inoculum
Cooked waste = 40.93%	Cow dung = 50%
Fruit waste = 19.63%	Digested Slurry= 50%
Vegetable waste = 39.45%	

Table 7: Feedstock Characteristics

Parameters (%)	Food Waste	Slurry	Cow Dung	Substrate + Inoculum
Moisture Content	78.37	91.17	80.8	80.52
Total Solids	21.61	8.83	19.7	19.48

Volatile Solids	78.7	61.6	61.4	64.7
Total Organic Carbon	45.65	35.73	35.62	37.53