Design of Small Scale Biogas Digester for Rural Community

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Session 2015-17

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THESIS ACCEPTANCE CERTIFICATE

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Abstract

Rural communities in developing countries run a major energy deficit and are inevitably in need of cost effective technological solutions. Acquisition of biogas technology provides the sustainable solutions to rural communities of the developing countries. Opportunistically, agricultural waste is abundant in the rural areas which can be used as a source for Biomethane production this study focuses on the design of renewable biogas system for rural community deploying agricultural waste for anaerobic co-digestion. An anaerobic digester of $3m^3$ volume was designed that will provide sufficient energy for one household. Selection of lignocellulosic waste Wheat Straw (WS), Rice Straw (RS) and Bagasse (BA) is based on the potential bioenergy and abundant availability of crops reported in the Biomass Atlas of Pakistan. Biochemical Methane potential test (BMP) was conducted for the evaluation of feed to inoculum ratio of ratios (1.5, 2.5) and four possible combinations (WSRS, RSBA, BAWS, WSRSBA). 70% biomethane production was investigated from combinations of WSRS and WSRSBA.

Keywords:

Anaerobic digester, Lignocellulosic waste, biomass atlas, anaerobic co-digestion, Gas Chromatography, Biochemical methane potential

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List of Abbreviations

GC: gas chromatography

HRT: hydraulic retention time

OLR: organic loading rate

BMP: biomethane potential setup

GHG: green house gas

WS: wheat straw

RS: rice straw

BA: bagasse

TS: total solids

VS: volatile solids

List of Journal/Conference Papers

1. Saadia Meraj, Atoofa Zainab, Dr.Rabia Liaquat

Co-digestion and optimization of lignocellulosic residues for biomethane production in Anaerobic digestion

Presented in Conference papers presented in NanoSET conducted by COMSATS Lahore

2. Atoofa Zainab, Saadia Meraj, Dr.Rabia Liaquat

Investigation of natural waste materials as biofilm carriers for optimization of Anaerobic digestion

Presented in Conference papers presented in NanoSET conducted by COMSATS Lahore

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[1] Attached as Annexure I

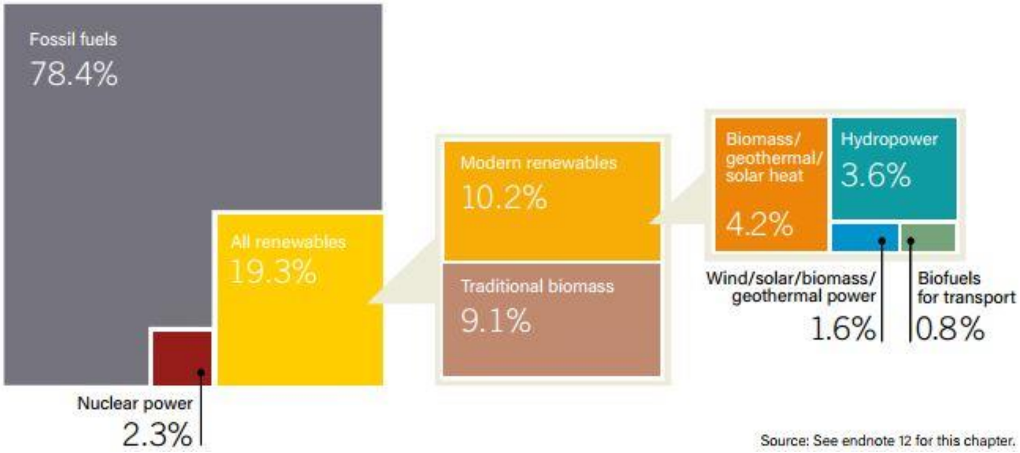
[2] Attached as Annexure

Chapter # 1

Introduction

1.1 Energy Scenario

Energy is an essential of life. Conventionally the energy was produced through the non-renewable energy resources (coal, oil, natural gas) now the renewable energy sources are being developed to produce energy. This global shift in energy systems occurred due to the depletion of the conventional energy resources and increase in environmental issues, scientists felt the need for the development of the alternative energy techniques based on the renewable energy resources for the benefit of the society.**[1]** Renewable energy resources include solar energy, bioenergy, wind energy, geothermal energy, fuel cell and batteries, figure 1 depicts the global energy mix and contribution of the renewable energy for energy production.**[2]**



Source: See endnote 12 for this chapter.

Figure 1.1 Global Energy mix [2]

The share of the renewable energy consumption has been increased, mostly used renewable resources are solar energy, biofuels, wind energy, hydropower. Researchers are improving technologies of other renewable resources to decrease the reliance on fossil fuels. **[3]**

1.2 Bio-Energy

Bioenergy offers promising alternative to conventional resources, biomass account for 80% production of the energy among renewables. The liquid and solid biomass equilaterally used for the fuel production additionally for heating and cooling, electricity production and transport fuel. Biomass conversion technologies have achieved conversion efficiency of 85% residential and 70% for commercial and industrial applications. **[4]** The numerous new bio energy technologies have been established which includes bioethanol, biomethane, biobutanol.**[5]** Existing technologies have been used and established by the developed countries while developing countries are also focusing to use these efficient ways the as source of fuel. Production of fuel are through the various well-developed technologies like anaerobic digestion, thermo-chemical, chemical and biochemical conversions. **[6]**

1.3 Anaerobic Digestion

Microbially produced biogas is an essential part of global carbon cycle natural degradation of biomass discharged tons of biogas annually in the atmosphere which is a source of global warming and making environmental conditions worse. **[7]** Biogas recovery system exploit these biochemical processes to decompose various types of biomass which potentially are source of energy the process is known as anaerobic digestion; anaerobic digestion of various substrates occurs in an anaerobic condition the waste is degraded by the anaerobic bacteria. There are some operating parameters which influence the anaerobic process such as pH, temperature, carbon to nitrogen ratio, hydraulic retention e (HRT) and organic loading rate (OLR). **[8][9]**

Anthropogenic anaerobic bioreactors recover the energy within the biogas, these reactors are specifically designed for the substrates which contained high proportion of anaerobic degradable biomass the substrates include, agricultural, sewage, industrial, municipal solid waste**.[7]** Among these substrates agricultural waste is difficult to digest due to their complex structure. Structure of agricultural waste comprises of cellulose, hemicellulose and lignin, among these lignin is hard to digest having a three-dimensional structure. These lignocellulosic materials undergo pretreatment to degrade the complex structures of biomass. There are different types of pretreatments which includes physical or mechanical pretreatment, chemical pretreatment and biological pretreatment thermal pretreatment. **[10] [11]**

1.4 Biogas production Plants in Developing Countries

Anaerobic digestion (AD) technology is used commercially around the world, especially in Europe, which has set some challenging targets to differentiate its energy mix with further renewable energy. Due to latest concerns there has been a tendency to adopts the sustainable energy production resources. The rural communities are rich with the biomass waste and the production of energy could be done through the already developed technologies. Biomethane production from the biomass is the easiest and cost-effective way that occurs according to the principle of Anaerobic digestion technology. Anaerobic digestion process occurs in an anaerobic condition developed in a reactor or digester and for betterment of the energy scenarios for the rural communities there is need for development of simplified, easy to use and cost-effective technology. Biogas technology is well developed in China and India. In China has about 6.8 million household digesters and 1000 medium and big size digesters till 2007 with an assessed production of 2 million cubic meter, producing 5% of total gas energy in China.

Biogas recovery system known as anaerobic reactors various anaerobic digesters have been developed and disseminated globally. Biogas digesters developed for the use of rural community of developing countries includes fixed dome biogas digesters, floating drum biogas digesters, plug flow biogas digesters.

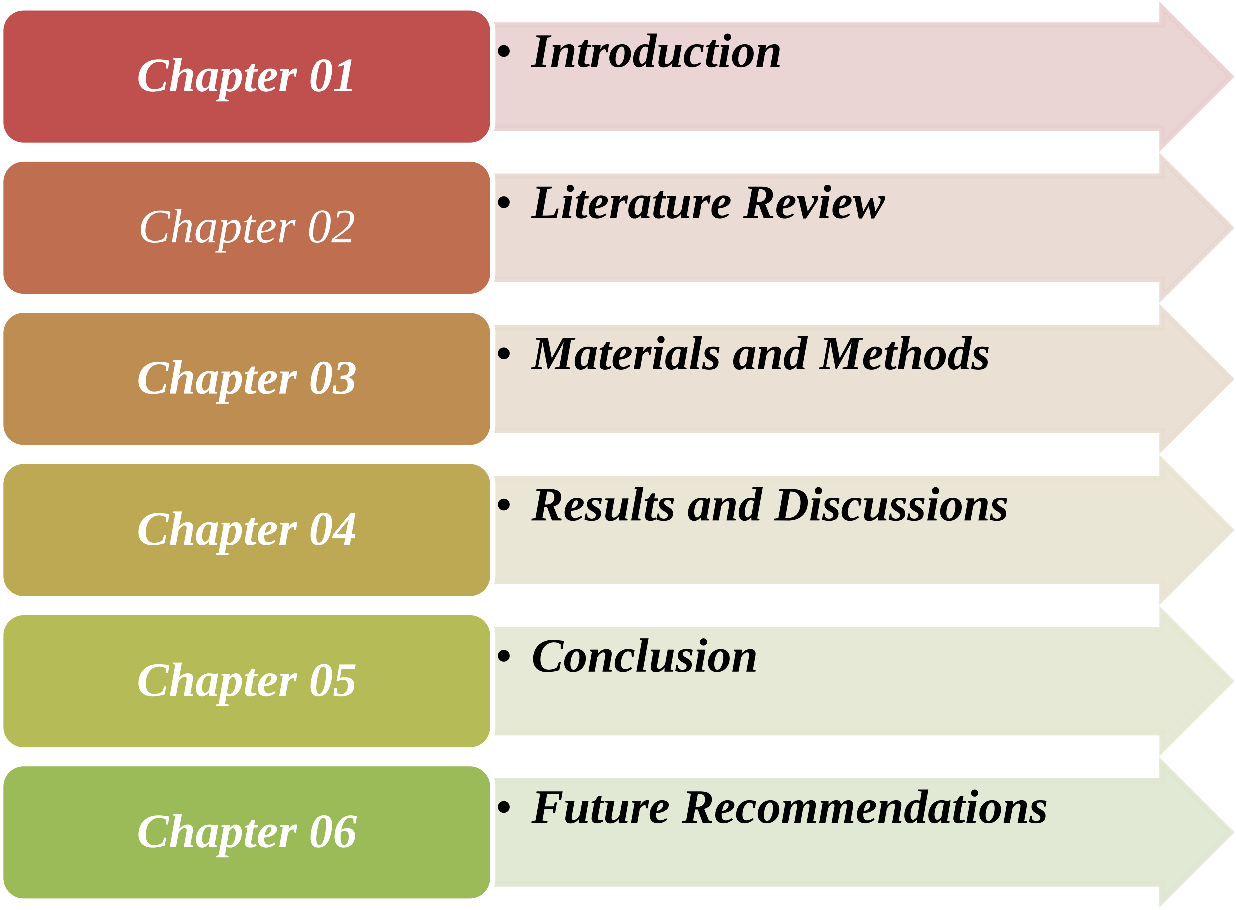
1.5 Aims and Objectives of Research

The study mentioned in this thesis has the following aims and objectives

1. Anaerobic Codigestion of wheat straw, rice straw and bagasse for biomethane production
2. Proposed design of small scale biogas digester for rural community
3. Economic Analysis of solar assisted Small-Scale Biogas Digester
4. Reduction in GHG Emissions

1.6 Thesis Structure

The structure of thesis is shown in the figure mentioned below



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Chapter # 02

Literature Review

2.1 Anaerobic Digestion Process, Technology and Operation

2.1.1 History of Anaerobic Digestion

In 1630, Jan Baptist van Helmont (1580–1644), studied that organic material in decomposition produced flammable gases. Few years later (1776), Alessandro Volta (1745–1827) discovered methane by collecting gas emerging from Lake Maggiore (Italy) and in 1804, John Dalton (1766–1844) developed the chemical composition of methane. The perception of anaerobic digestion was introduced in 1870 with the development of the septic tank system by Jean-Louis Mouras. It was Louis Pasteur (1822–1895) who reported that biogas could be used for heating and lighting. Indeed, in 1895 Donald Cameron design led to light up the streets of Exeter (England). Anaerobic digestion is auspicious alternative for energy production and it reduces the environmental problems. The substrates or biomass waste which are composed of proteins, fats, carbohydrates, hemicellulose and cellulose can be used for biogas production. Shortly, anaerobic digestion is the biological process in which the complex organic matter is decomposed by microorganisms in the absence of oxygen produces biogas. [1]

2.1.2 Composition of Biomethane

Biomethane (Biogas) is the composition of organic and inorganic materials. The composition of biogas varies certainly to some degrees because of the feedstock. Biomethane (Biogas) is majorly composed of methane and carbondioxide and traces of other compounds includes carbon monoxide, hydrogen sulphide, nitrogen, ammonia, hydrogen. [2]

Table 2.1 Composition of Biogas

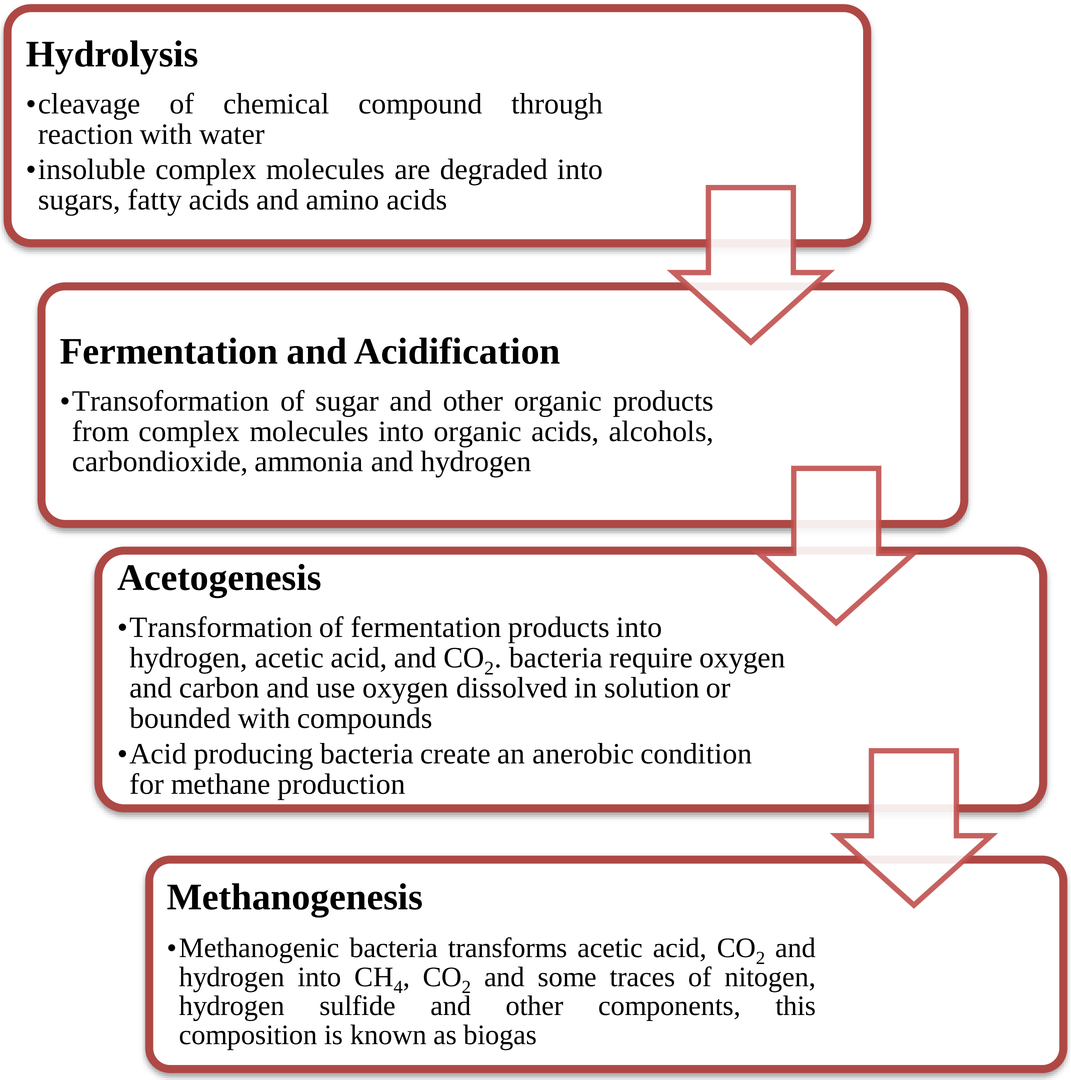
	Chemical Compound	Content (%)
1	Methane CH_4	50-75 %
2	Carbondioxide CO_2	25-45%
3	Hydrogen H_2	<1
4	Nitrogen N_2	<2
5	Ammonia NH_3	<1
6	Hydrogen sulphide H_2S	<1
7	Water vapors	2 (20°C) – 7 (40°C)

2.1.3 Anaerobic co-digestion

Anaerobic co-digestion is the anaerobic digestion process which uses pretreated multiple substrates for the generation of biomethane. methane production from anaerobic co-digestion strongly depends on the several factors pH, C/N ratio, temperature, nutrient content, particle size, C/P ratio.[3] [4] If the proper conditions are disturbed it will lower the performance and would marks the failure of the process. Imbalanced nutrient in anaerobic digestion is the restraint of the process therefore to balance the nutrient ratio the anaerobic co-digestion process is implemented. Anaerobic Co-digestion technology provides the opportunity to balance the nutrients and improves the production. [5][6]

2.1.4 Biochemical Process of Anaerobic Digestion and Co-digestion

The conversion pathways for organic substrate degradation is similar for both anaerobic digestion and Anaerobic co-digestion. The process is carried out in four



Hydrolysis

- cleavage of chemical compound through reaction with water
- insoluble complex molecules are degraded into sugars, fatty acids and amino acids

Fermentation and Acidification

- Transoformation of sugar and other organic products from complex molecules into organic acids, alcohols, carbondioxide, ammonia and hydrogen

Acetogenesis

- Transformation of fermentation products into hydrogen, acetic acid, and CO_2. bacteria require oxygen and carbon and use oxygen dissolved in solution or bounded with compounds
- Acid producing bacteria create an anerobic condition for methane production

Methanogenesis

- Methanogenic bacteria transforms acetic acid, CO_2 and hydrogen into CH_4, CO_2 and some traces of nitogen, hydrogen sulfide and other components, this composition is known as biogas

Figure 2.1 : Anaerobic digestion Processes [7] [8] [9] [4]

2.1.5 Factors Affecting Anaerobic Co-digestion

Anaerobic co-digestion involves microorganisms for the degradation of the organic waste a group of microorganisms such as actinomyces, Thermomonospora, Ralstonia and Shewanella are involved in the degradation of waste into VFA’s, but Methanosarcina and Methanobrevibacter/Methanobacterium mainly contribute in methane production. These microorganisms necessitate specific conditions to produce biomethane. The factors which effects the performance of the bacteria and biomethane production yield are described below in detail

2.1.5.1 Temperature

Temperature is an effective parameter for the anaerobic digestion and it effects the methane production. There are three different temperature zones that can distinguish the bacterial growth

- Psychrophilic zone (temperature < 20°C)
- Mesophilic zone (temperature ranges from 25°C – 35°C)
- Thermophilic zone (temperature >45°C)

Temperature above 70C the bacterial population becomes inactive due to denaturation of enzymes. Low temperature inhibits bacterial growth and decrease the biomethane production. The anaerobic digestion generally carried out at mesophilic conditions reaction is more stable with low energy requirement. 35-37°C is considered as the appropriate temperature to produce the biogas, the shift from mesophilic to thermophilic will cause the reduction in the biogas yield unless there is an increase in the necessarily bacterial production. Thermophilic temperature has faster reaction rates, having higher productivity than mesophilic bacteria, acidification in the thermophilic process exhibit the biogas yield. Thermophilic reactions have some other disadvantages like low stability, increased toxicity, low quality effluent, high energy input, large investments, susceptible to environmental conditions and poor methanogenesis. Decrease in temperature would results in VFA degradation, ammonia concentration and substrate. The optimal conditions in anaerobic digestion can be mesophilic methanogenesis and thermophilic hydrolysis or acidogenesis. [10] [11] [12]

2.1.5.2 pH

The optimal pH value in the anaerobic digestion process would be 7.0, and it is reported that the pH ranges from 6.8-7.2 is ideal. The growth of microorganism's changes with the value of the pH. It has been observed that methanogenesis occurs at the pH of 6.5-8.5, acidogenesis at the value of 6.5 whereas hydrolysis at pH of value 5.5.[11] [13]The reactors with initial pH 9.0 would give maximum hydrogen production.[14] The decrease in anaerobic digestion would be at the pH below than 6.0. [15]

2.1.5.3 Carbon to Nitrogen Ratio

Carbon to nitrogen ratio is a sensitive parameter and it must be balanced for production of biogas. C/N ratio strongly depends on the type of substrate being chosen for the digestion process. Before the start of the digestion process the substrate should be characterized for the determination of the carbon and nitrogen content, to adjust the C/N ratio for the better methane production. The optimal value of the C/N ratio is 20-30:1. This shows that the concentration of carbon should be 25 to 30 times more than the nitrogen. Lower values of the carbon to nitrogen ratio would result in ammonia accumulation which constrain methane production, higher C/N ratio would result in nitrogen consumption during startup phase of anaerobic digestion process keeping in view these factors optimization of C/N ratio is very important. Optimum C/N ratio regulates the nutrient balance for the methanogens for enhancement in methane production. [16] [17]

2.1.5.4 Organic Loading Rate

OLR is the amount of volatile solids added into a digester per day under continuous feeding. With increasing OLR, the biogas yield increases to some extent, but this disturbs the balance and efficiency of the digester. [18] Daily addition of OLR would limit the hydrolysis, methanogenesis and increase the VFA accumulation. The increase in VFA accumulation inhibit methane production. The increase in organic loading rate is suitable with the thermophilic system. [19][20]

2.1.5.5 Hydraulic Retention Time

The hydraulic retention time is the time needed to complete the degradation of organic matter. HRT depend on the microbial growth rate, temperature, OLR and substrate composition. Two significant types of retention time are discussed generally HRT and SRT. SRT is the average time that solids spend in a digester.[10]

HRT = V/Q

Where V = reactor volume

Q = influent flow rate

It is reported that average HRT under mesophilic conditions is 15-30 days, decrease in HRT would lead to VFAs accumulation. The best condition for significant biomethane production is the low organic loading rate and long HRT.[21] [10]

2.2 Substrates used in Anaerobic Digestion

Biomethane production from various substrates has been studied by the scientists, the organic matter or biomass commonly used for anaerobic digestion are municipal solid waste, agricultural waste, food waste (vegetable, fruit waste), sewage sludge and may other the organic matter used as a substrate in this study is lignocellulosic waste also known as agricultural waste. [22]

2.2.1 Lignocellulosic Material

Lignocellulosic waste is biomass used to produce alternative fuel known as biofuel, could be used to produce both bioethanol and biomethane as a source of energy. Wood, agricultural residues, grass, forest residues and energy crops are all lignocellulosic waste. Lignocellulosic wastes are difficult to digest due to their complex structure. [23]

2.2.1.2 Structure of Lignocellulosic Material

Structure of Lignocellulosic material is constituting of three components

1. lignin (10-25%),
2. cellulose (38-50%) and
3. hemicellulose (23-32%).

Cellulose in a plant consist of either amorphous structure or crystalline structure. Cellulose are combined in the form of cellulose fibrils; these cellulose fibrils are independent or weakly bounded with hydrogen bonding. [24] Hemicellulose is rigid to digest it act as a linkage between cellulose and lignin. Hemicellulose have low digestibility and passes undigested through the anaerobic digestion processes. Lignin is the major component of the plant cell wall and it endow the structural support, impermeability and resists the microbial attack and is recalcitrant to digest by microbes for renewable biochemical conversion. It is non- soluble in water. [25]

2.2.1.3 Pretreatment Methods for Lignocellulosic Waste

Lignocellulosic materials have complex and rigid structure and requires long time for degradation, the complex structure and lignin content of lignocellulosic biomass create recalcitrance in Anaerobic Codigestion, the selection and use of appropriate pretreatment method will shorten the time of degradation and overcome the limiting step of substrate hydrolysis by enhancing the enzymatic degradability of lignocellulosic biomass and by cumulative the biogas yield. [26]

Lignocellulosic wastes are pretreated with different methods shown in the figure below [27] The pretreatment Method used in this study is physical or mechanical pretreatment.

2.2.1.4 Mechanical Pretreatment

The objective of mechanical pretreatment is the reduction of size and crystallinity of lignocellulosic material. Mechanical pretreatment is given by grinding, hammer mill, knife mill, ball milling. For the reduction of particle size, the grinders are used to reduce the crystallinity of the substrate and increase the porosity of the substrate so that it could be easily degraded by the anaerobic bacteria. The decrease in particle size leads to an increase of available specific surface and a decrease degree of polymerization (DP).The milling causes also shearing of the biomass. [28] pore volume or porosity of lignocellulosic material enhance the initial enzymatic hydrolysis rate. Increase in digestibility takes place when the pore size of substrate is large to easily accommodate both large and small enzymes.[29]

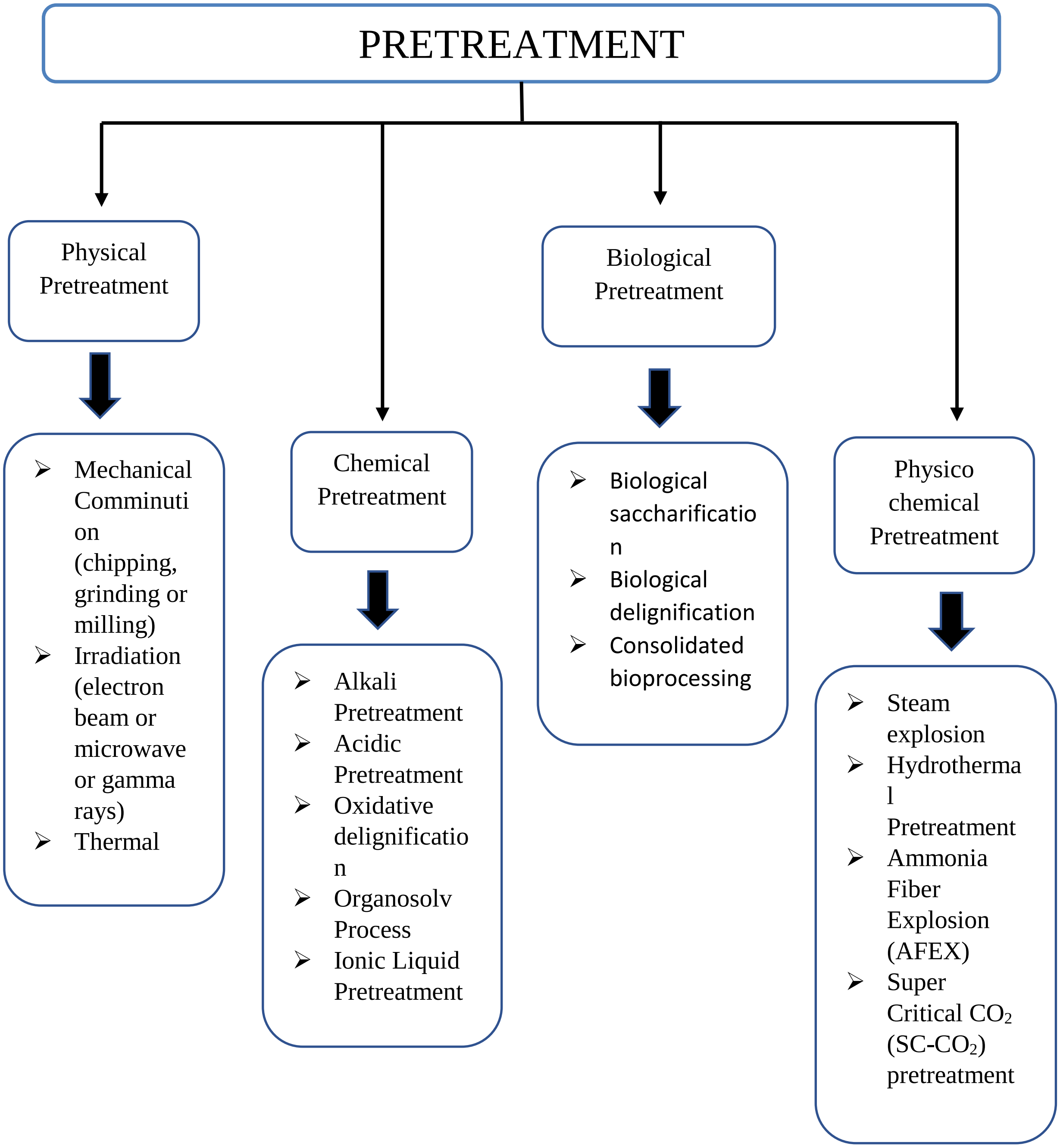


Figure 2.2: Pretreatment Methods for Lignocellulosic Material [27] [29]

2.3 Anaerobic Digestion Technologies

Anaerobic digestion technology is recognized globally and is energy efficient, environmental friendly technology. If handled properly this technology can be adopted by the rural community because of its affordability and environmental benefits. Various designs of biogas digesters have already been in the market and adopted by the rural communities, industrially and by agricultural farm. The rural household biogas is an important strategy to promote agricultural structure , reduction of waste, increase rural income, improves environmental conditions and act as source of energy production. [30] The selection of the digester depends on the type of waste from which the biogas could be produced. Among many digesters design the few digesters used in the rural community are

- Floating drum digesters
- Fixed dome digesters
- Tubular digesters
- Garage type digesters [31]

They are small system biogas plants these digesters are the simple digesters different from the temperate region, easy to use and lack the stirring and heating facilities.

2.3.1 Floating Drum Digesters

In 1960 the floating drum Hindu style model (figure 2) was developed in India comprises of cylindrical or dome shaped digester, moveable and gas holder is present in upper section. Plants are either constructed using the concrete or the drum could be used of the steel. The gas storage drum is placed at the top of the digester and is used for the gas collection. The gas drum is moveable it moves up and down depending upon the amount of gas present, the weight of the gas applies pressure that is required for the gas flow. Feed is added daily along with water. Floating drum provides the gas at the constant pressure and the volume of the gas could be known easily. These digesters could be built within the ground or above the ground. The initial investment cost of the digester is very high, and the maintenance cost is huge due to the use of paints on the metallic dome for avoiding rusting. The construction materials might not always be available, the labor is required for the digesters construction. Digesters could be built of the volume 1.6 m^3 – $10m^3$ and the larger digesters are constructed of size 6- 10 m^3. These digesters have small lifespan, life span of the gas drum is 5 years and of all the system is 15 years. [31][30]

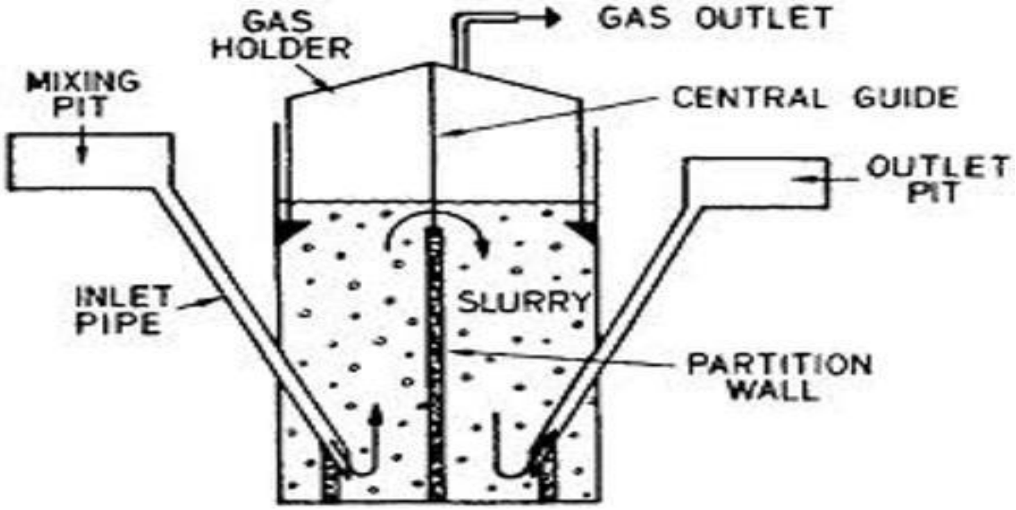


Figure 2.3: Floating dome biogas digesters [29]

2.3.2 Fixed Dome Biogas Digesters

The fixed dome digesters are dome shaped, immoveable digesters gas holders with feedstock inlet and digestate outlet (figure 3). The digestate outlet could also be named

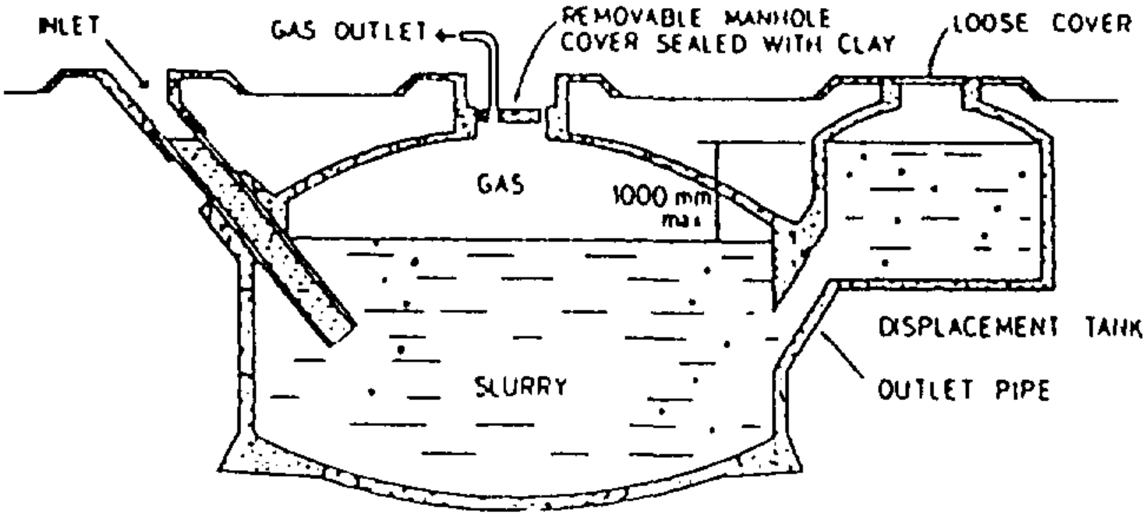


Figure 2.4 : Fixed Dome Biogas Digester [32]

as the compensation tank, construction materials used for biogas digesters are the bricks and concrete which would have severe leakage issue so use of paints or water proof layer. The production of biogas starts the slurry gets placed in the compensation tank. In fixed dome digesters when the gas is extracted the slurry automatically goes into the digester from the compensation tank. Gas pressure unlike floating drum is not constant and it increased with the amount of gas stored and the height difference among two slurry values. Fixed dome plants could handle the fibrous materials, with the animal manure the motion of the substrate could break the scum layer. Generally, the feed is added continuously in the plant, but if the pit is large the feed could be added once for few days. The initial investment cost is less, and the operational cost is high. The lifespan of the digester is 15-20 years if non-moveable parts are present. There are several models of fixed dome biogas plants which includes Chinese fixed dome plant, Indian Deebandhu, Akut and the CAMARTEC model each having the hemispherical dome shell structure as the central feature. Commonly used designs are CAMARTEC model and AKUT. [22][32]

2.3.3 Plug flow digesters

Plug flow digesters (figure 4) are weather resistant, heat sealed usually reinforced HDPE plastic or rubber bag. The digesters comprise of two parts the lower part is the slurry portion and the upper part is the gas portion having the inlet and outlets. The pressure

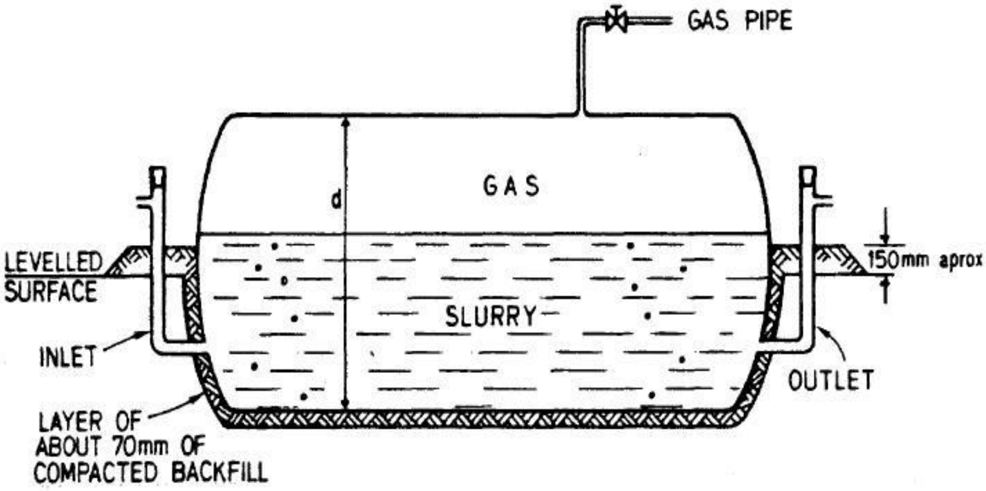


Figure 2.5 : Plug flow or tubular digesters [33]

would be achieved by placing the weight on the digester. The balloon type digester is fragile and vulnerable to mechanical damage, the feed capacity is less as compared to floating drum and fixed dome digesters. Plug flow digesters are resistant towards extreme climatic conditions. These digesters are low cost and could be easily installed but their lifespan is quiet short of 2-5 years. [33][32]

2.4 Small Scale Biogas Digester's Scenario in Pakistan

Pakistan is amongst those developing countries facing severe issues of poverty, population pressures and energy shortage. On average now, the people of Pakistan are facing power cuts of up-to 10–14 h per day. [34] The solution to these problems is the investments and development in renewable and sustainable energy technologies like biogas and bioenergy. Biogas is a methane rich gas that is being generated by anaerobic fermentation of organic material and a biogas plant can efficiently utilize numerous feed sources which includes animal manure, food waste (vegetable, fruit waste), sugar, poultry waste and agricultural waste. [35]

Domestic installation of biogas plants has been started in 1959 in Sindh and then Biogas Support Program (BSP) was in progress in year 2000 by Government of Pakistan for domestic biogas units and so far, 1200 Nos. biogas units, were installed and functional under the program. Whereas there is a goal to install other 10,000 units. Currently Pakistan Dairy Development Company (PDDC) has installed biogas units' installation in its Horizon-3 initiative with an aim to provide alternate renewable energy at very low cost to rural groups, Until May 13, 2009 around 450 biogas plants were installed additionally due to positive response of people the number increased from 450 to 556 implementations occur after July 2009. The companies which are involved in the installation of biogas plants in rural areas or anywhere else in Pakistan are PCRET, RSPN, Pakistan Council of Scientific and Industrial Research (PCSIR), Punjab Agriculture Department both in Lahore and Faisalabad. Considering the economics of the biogas digesters an average household scale biogas plant of 10 m^3 saves 92,062 PKR per year considering conventional methods of fuel. [36]. The biogas digesters normally installed in rural communities' ranges from $3m^3$ to $5m^3$. The most common type of digesters installed in Pakistan with certain improvements includes floating drum biogas digesters, fixed dome biogas digesters, tubular or plug flow biogas digesters. These biogas plants installed have faced certain failures most commonly observed failure was the leakage of biogas and others include inappropriate handling of biogas digesters, lower maintenance of the biogas digesters. [37][36]

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Chapter # 03

Materials and Methods

3.1 Methodology or Roadmap of Research

The methodology adopted for this study is mentioned in figure below. Firstly, the substrate and inoculum were selected, following the substrate selection of the lignocellulosic material was based on availability and potential of the material for biomethane production. Selected lignocellulosic material must be given pretreatment for enhancement in methane production keeping in view that the best methane production ratio must be added in the anaerobic digester which would be operated by the rural people, we have selected the mechanical pretreatment that could be easily adopted by the rural community.

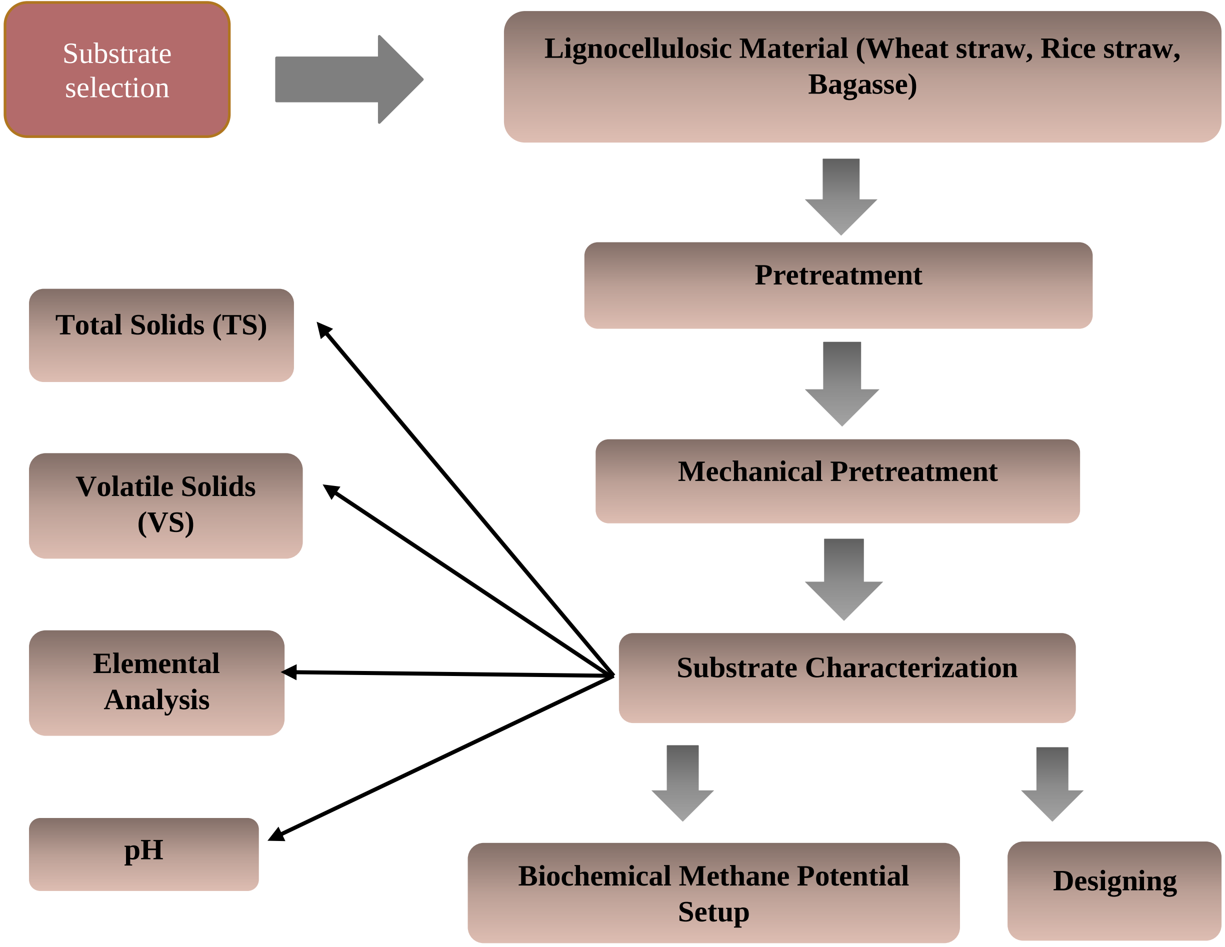

Figure 3.2 Road Map of Research

3.2 Schematics of Biochemical Methane Potential

Biochemical Methane potential setup was established to analyze the potential of three substrates by forming different combinations. The experiment was conducted for two ratios 1.5 and 2.5. The biogas formed was analyzed by the gas chromatograph and then the Gompertz model was applied for verification of the results.

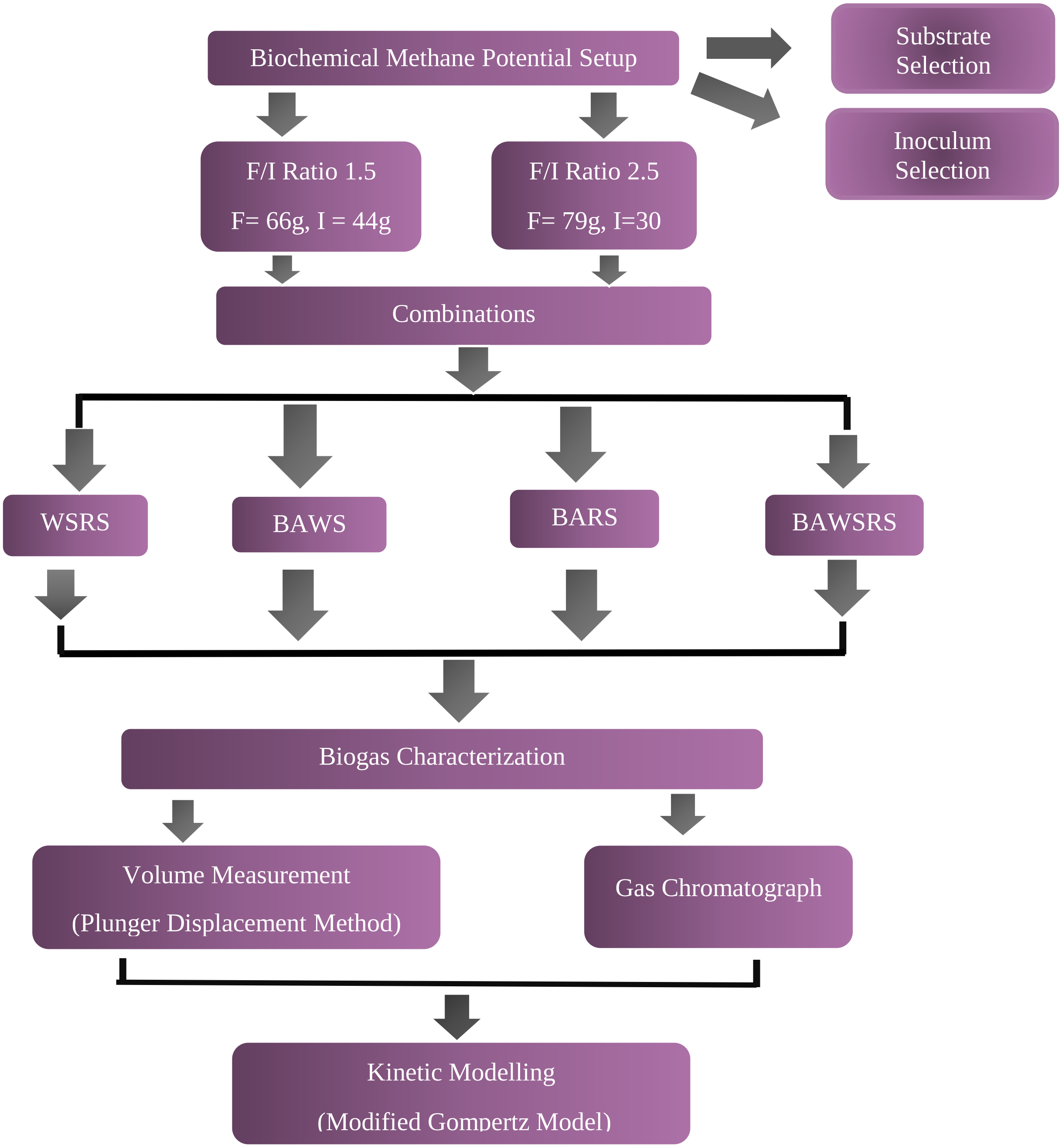

Figure 3.2 Biochemical Methane Potential Setup

3.3 Experimental Section

3.3.1 Substrate and Inocula

Wheat straw, Rice straw and Bagasse are used as the substrate in this study. These materials were selected according to the biomass atlas of Pakistan [1] because of their high theoretical and practical potential and willingness of farmers to sell this waste and were collected from the local areas of Pakistan. The Inocula used in this study was the digestate of the Digester undergoing anaerobic co-digestion of Dairy waste and different type of food waste. The digester was operational under mesophilic conditions. The Inocula was stored at 4°C after collection from the digester and then before the use of the Inocula degassed it and it was kept at 35°C for five days.[2]

3.2.2 Substrate Pre-treatment

The agricultural waste was manually screened by removing unnecessary materials. Substrates were Mechanically pretreated for size reduction agricultural residues were reduced manually to the size of 10cm by means of scissor and then the reduced waste was further grinded. The size was reduced to 1cm after grinding.

3.2.3 Lab- Scale Biochemical Methane Potential Setup (BMP)

BMP assays were established to analyze the methane composition in the biogas. [6] [7] Batch experiment were performed to analyze the biogas production of the selected substrate in the laboratory. Mesophilic conditions were provided to the reactors. The co-digestion of agricultural residues and inoculum (digestate of the operational digester) was examined in the glass bottle with the capacity of 300ml and 210ml working volume of the reactor. Substrates, inoculum and water were added as the feed of the batch digester. The bottles were properly sealed with the rubber stopper with an insertion of syringe of volume 25ml. Combinations of the selected materials with three different ratios were made and methane production was analyzed. Possibly four combinations were made, and they were WSRS, BAWS, RSBA, BAWSRS the ratios selected were 1.5 and 2.5. The controls for every ratio comprises of inoculum and water.

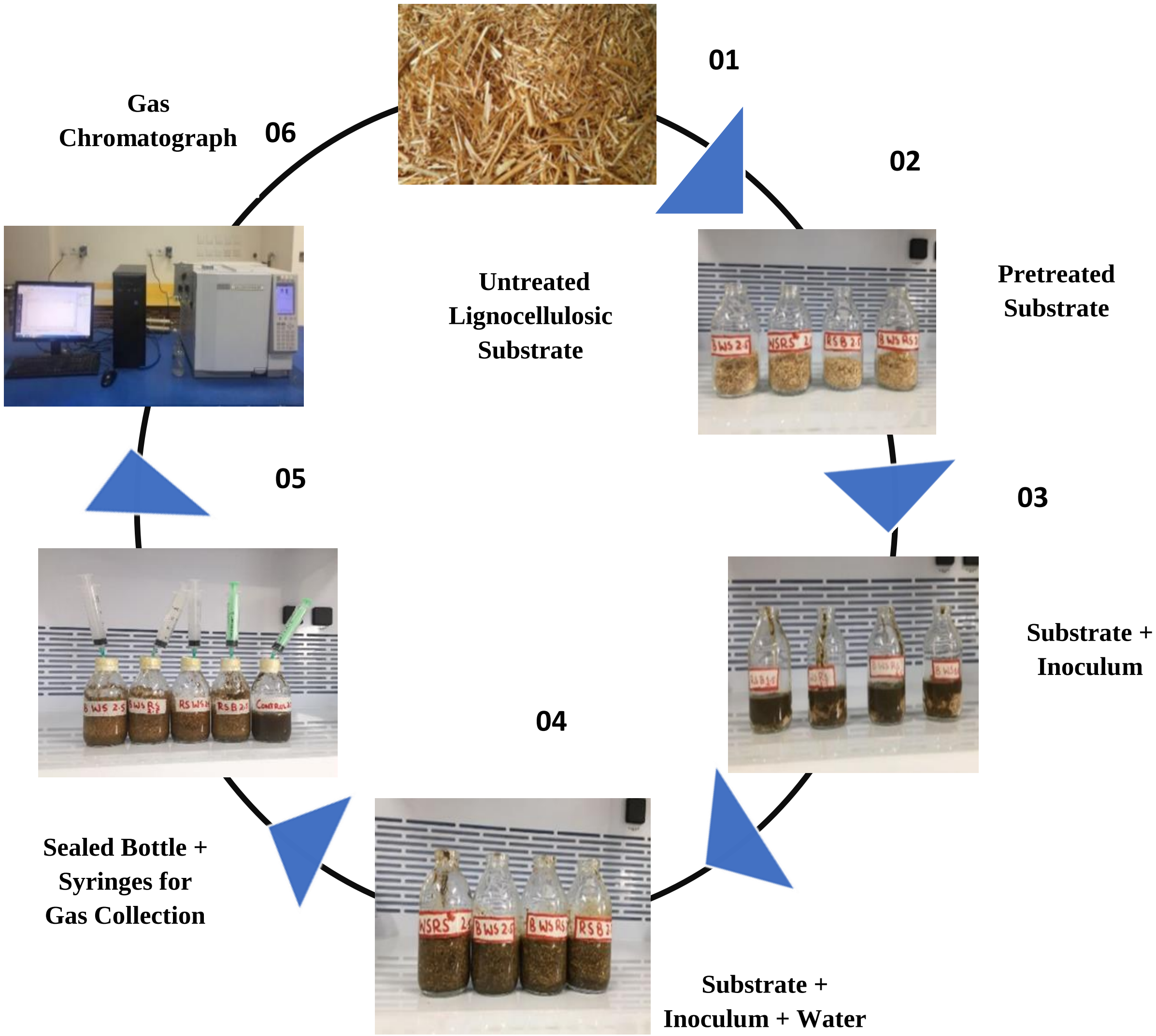

Figure 3.3: Lab-Scale Biochemical Methane Potential Setup

3.3 Analytical Methods

3.3.1 Proximate Analysis

Volatile solids (VS) and Total solids (TS) were calculated initially and at the end of the experiment using APHA method. [3] pH of the reactors was analyzed in the start and at the end of the experiment. pH was measured by using the Hannah pH meter model no HI 9829-01102. Total organic solids were evaluated by using the relation VS/1.8.

3.3.1.1 Determination of Total solids

To determine total solids empty weight of the crucible is first determined. Approximately 5g – 10g of the samples are added and then the samples are weighed again after weighing the samples the samples are dried using the drying oven at the 103°C to 105°C. After drying sample was placed in the desiccator cooled and then weighed again

Formula for calculating total solids is mentioned in equation (1)

$$\textbf{Total solids (TS)} = 100 * \frac{m_3 - m_1}{m_2 - m_1} \text{ -- } (1)$$

Where

m_1 = mass of empty crucible

m_2 = mass of crucible after sample added

m_3 = mass of crucible after drying

3.3.1.2 Method for calculation of Volatile Solids

To determine total solids empty weight of the crucible is first determined. Approximately 5g – 10g of the samples are added and then the samples are weighed again after weighing the samples the samples are dried using the drying oven at the 103°C to 105°C. After drying sample was placed in the desiccator cooled and then weighed again. And then the sample is ignited in the muffle furnace at 550°C. Later the samples are placed in the desiccator and then weighed again once they are cooled.

Formula for calculating the volatile solids is mentioned in equation (2)

$$\textbf{Volatile Solids (VS)} = 100 * \frac{m_3 - m_4}{m_2 - m_1} \quad \text{--} \quad (2)$$

Where

m_1 = mass of empty crucible

m_2 = mass of crucible after sample added

m_3 = mass of crucible after drying

m_4 = mass of crucible after ignition at 550°C

Table 3.1 Proximate Analysis of different combinations

Parameters	Wheat Straw	Rice Straw	Bagasse
Total Solids %	99	98.5	98
Volatile Solids %	83.33	62.42	80
Total Organic Carbon %	46.294	34.467	44.44
Moisture Content %	1	1.5	2

3.3.2 Ultimate Analysis

Elemental analysis of the wastes and inoculum was performed using the SEM/EDS. The determination of the Carbon, nitrogen, hydrogen, oxygen. Mentioned in table 2.

The C/N ratios of multiple substrates is calculated from the following formula **[4]** mentioned in equation 1

$$\frac{C}{N}\text{ Total} = \frac{C_1X_1 + C_2X_2 + C_3X_3 + \ldots\ldots}{N_1X_1 + N_2X_2 + N_3X_3 + \ldots\ldots} \text{ --- Eq (3)}$$

$$\frac{C_{\text{Total}}}{N} = \frac{\sum CiXi}{\sum NiXi}$$

C (% TS) and N (% TS) is the mass fraction of nitrogen in an individual material, and X_n (g TS) is the amount of the individual material in the mix (n = 1,2,3. . . i).

Table 3.2 Ultimate Analysis of Substrates

Substrates	C%	N%	H%	O%	C/N
Wheat straw	52.21	1.6	5.90	33.94	32.631
Rice straw	30.2	1.36	6.1	59.6	23.23
Bagasse	13.6	0.9	5.38	33.1	15

3.3.3 Biogas Characterization

Biogas was collected in the syringes and then volume measured by the plunger displacement method. Methane content present in the biogas was analyzed by using the gas chromatograph Shimadzu 2010 plus equipped with column of RT-MS5A (TCD). The temperature setting for the column is maximum temperature was 300°C, temperature equilibrium time was 3 min starting from 35°C (2min). Helium is used as the carrier gas at flow rate of 30 ml/ min. Biogas was injected manually using a syringe of 25ml.

3.4 Framework for Designing of Biogas Digester

Figure 3 shows the framework for designing of biogas digester which is explained further in the next section.

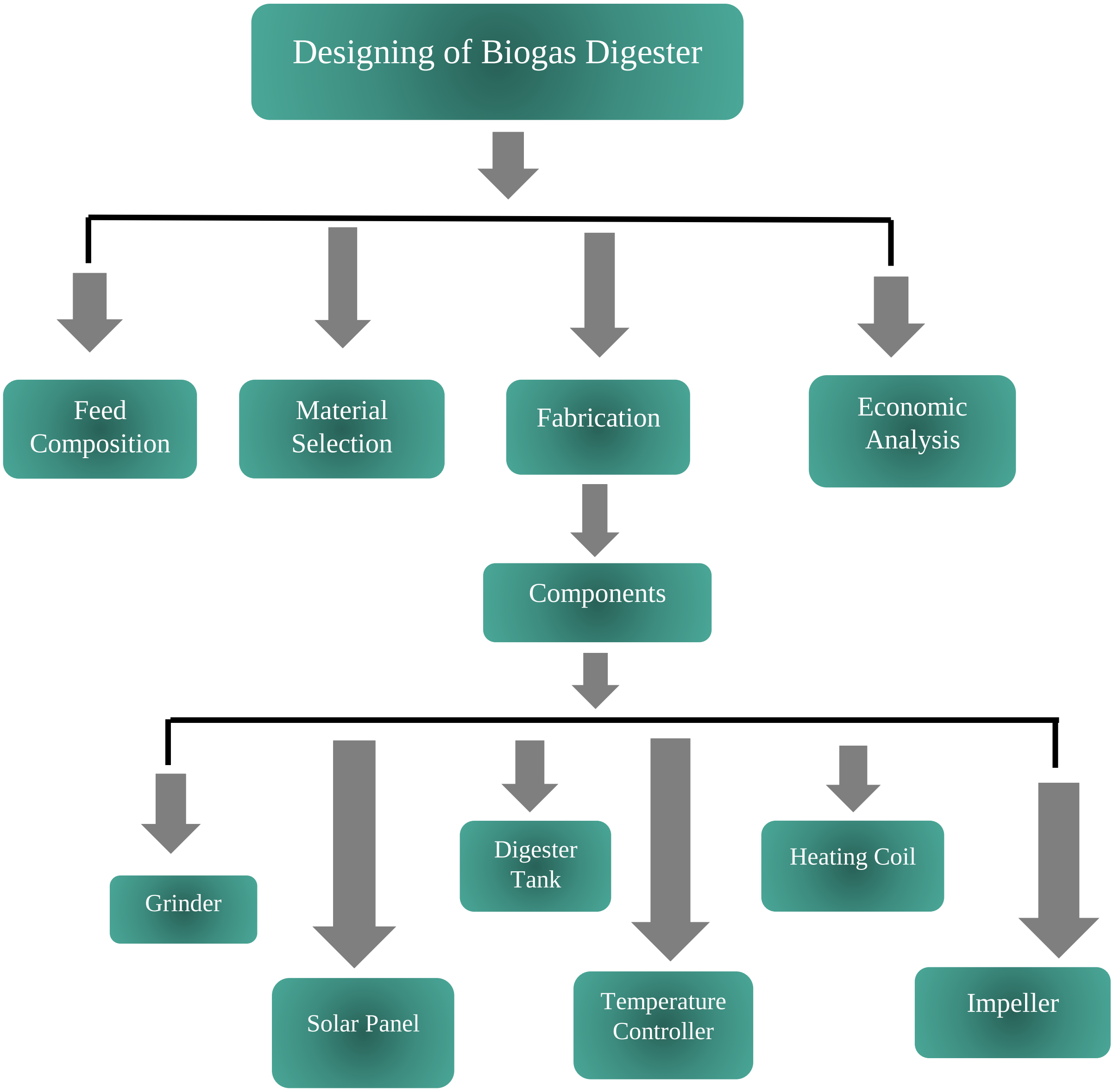

Figure 3.4 Framework of designing of biogas digester

3.5 Designing of the solar assisted biogas Digester

Design of small scale biogas digester constitute of following

3.5.1 Feed Composition

The best combination of substrates with highest methane production was selected after evaluating the potential from the experiment. WSRS with ratio 1.5 have given the best biomethane production among all combinations from both ratios, so WSRS would be suggested as the feed in the anaerobic biogas digester for biomethane generation.

3.5.2 Material Selection

Material selected for the fabrication of biogas digester was on the basis of corrosion resistivity, heat resistant, durability and considering other physical, mechanical, thermal and electrical properties of the material the stainless steel of grade 316 was selected as the material for fabrication.

3.5.3 Fabrication of Anaerobic biogas digester

Anaerobic biogas digester comprises of the following components

- Grinder
- Solar Panel
- Digester Tank
- Baffles
- Impeller
- Heating Coil
- Temperature Controller

3.5.3.1 Digester Tank

Cylindrical shape digester tank would be made of stainless steel 316 grade which is corrosion resistant and have a life expectancy of more than 30 years for aqueous environment as the anaerobic digestion itself is a wet biochemical process. [8] [9][10]

3.5.3.1.1 Dimensions of Digester tank

Volume (V) = $\pi r^2 h$

Where r is the radius of the cylinder and h is the height of the cylinder

Let volume of digester tank be $3m^3$ as small-scale biogas digesters are ranged between $3m^3 – 5m^3$

V = $3m^3$

r = 0.4 m   D = 2r = 0.8m and D = T = 0.8 m

h = 5.971 m ~ 6 m

Feed Inlet pipe diameter = I_D = 0.2 m

Feed Inlet Pipe Length = I_L = 4.8 m

Placement of Digestate disposal pipe from bottom of the cylinder = D_p = 1.2 m

Diameter of the digestate disposal pipe = D_d = 0.3m

Length of the digestate disposal pipe = D_L = 0.15*6 = 0.9m

3.5.3.2 Hydrofoil Impeller

Impellers are utilized to produce centrifugal force to create the mass transfer between the various phases by mixing. Mixing of phases can be accomplished and by which mass and heat transfer can be enhanced between phases or external surfaces. The operation of agitation, is efficient and well established for the chemical processes. Various factors affect the mixing efficiency such as baffles, impeller speed, impeller type, clearance, tank geometry, solubility of substance, eccentricity of the impeller. Flow patterns can be changed according to the type of impellers, and fall into three categories: axial, radial and tangential. Mixing at high solid concentration is an important procedure in process engineering. Solid-liquid mixing plays an important role in chemical, biochemical and mining processes. [11]

Local analysis of the flow in the tank could be done either experimentally or numerically using Computational fluid dynamics. Dimensions of hydrofoil impeller used in this study is based on the work of Greme L lane in which he confirms his results both experimentally and through CFD. [12] [13] The hydrofoil impeller is chosen for the mixing of the substrates due to property of having axial flow, less power consumption and efficient mixing quality impellers would be rotated after specific intervals.

3.5.3.2.2 Dimensions of Hydrofoil Impeller

Hydrofoil Impeller (Axial flow)

No of baffles = 2

Baffles = B = $\frac{T}{10}$

B = 0.08 m

Impeller diameter = D = $\frac{T}{3}$ = 0.2667 m

Clearance from bottom of the tank = C = D = 0.2667 m

Impeller Speed = N = 300 rpm => N = 5 s^{-1}

Tip Velocity = U_{tip}

U_{tip} = πND = 3.14*5 s^{-1}*0.2667 m/s = 4.18719 m/s

Power of the impeller = 2πNŤ = Ť = torque = 1.608 Nm

Power no = Np = $\frac{\boldsymbol{p}}{\text{Ƥ}\boldsymbol{n3D5}}$, Np = 0.3

Power = P = 2πNŤ = 10.09824 W

Table 3.3 Dimensions of components of Anaerobic Biogas Digester

Parameters	Digester Tank	Digestate pipe	Feed Inlet pipe	Hydrofoil Impeller
Length (m)	**6**	**0.9**	**4.8**	
Diameter (m)	**0.8**	**0.3**	**0.2**	**0.2667**
Rpm	**-**	**-**	**-**	**300**
Power (W)	**-**	**-**	**-**	**10.09**
Clearance (m)	**-**	**-**	**-**	**0.2667**

3.5.4 Operational parameters of the Biogas Digester

Operational parameters in anaerobic digestion process includes temperature, hydraulic retention time, organic loading rate and pH, the operational parameters are discussed below

3.5.4.1 Temperature

Temperature of the digester will be mesophilic ranged from 30°C-35°C. Temperature would be controlled and maintained by the temperature controller.

3.5.4.2 Hydraulic Retention time

HRT = V/Q

Where V = total volume of the reactor

Q = amount of feed in the reactor

Let HRT = 30 days

30 days = $3m^3$ / Q

Q = 3/30 m^3/day

Q = 0.1 m^3 /day

$Q = 100$ kg/day

3.5.4.3 Organic Loading Rate

OLR = m*C/V

Where m = Q = mass of substrate fed per day (kg/d)

C = concentration of organic matter

V = volume of digester

OLR for Feed WSRS

OLR = (100 kg/d * 0.72686)/ 3 m^3

OLR = 24.2268 kg/d.m^3

OLR for inoculum

OLR = (100 kg/d * 0.37844)/ 3m^3

OLR = 12

OLR for both WSRS + Inoculum

OLR = 24.2268 + 12.

OLR = 36.8433 kg/d .m^3

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Chapter # 04

Results and Discussion

In this study the Design of small scale anaerobic digesters was proposed for the rural community to overcome the energy shortage issue. The feed or material which rural community will utilize in anaerobic digesters for biomethane production was suggested based on results mentioned in this section.

4.1 Batch Scale Anaerobic Codigestion Biomethane Potential of Substrates

Biogas produced from different combinations of wheat straw, rice straw and bagasse were analyzed by GC (Shimadzu 2010 plus) twice in a week for determination of methane content. The biogas production was observed for 60 days still there was the tendency for biomethane production. Methane production trend of different

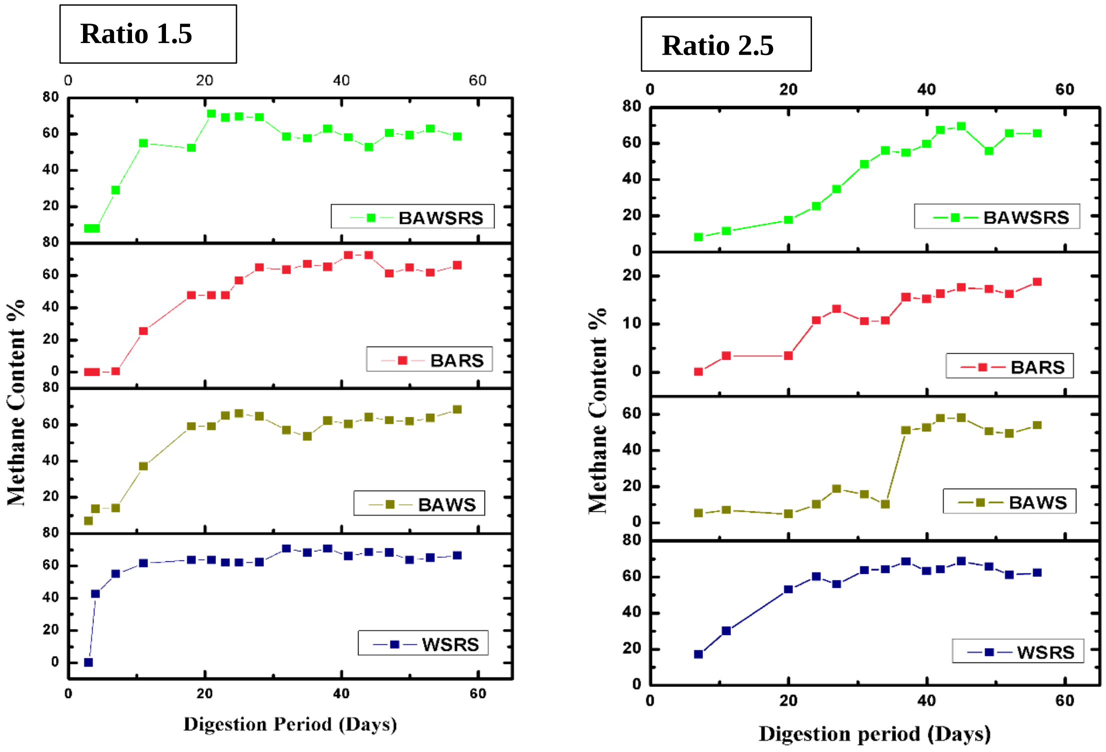

Figure 4. 1**: Methane Production from different combinations of 1.5 (a) and 2.5 Ratios (b)**

combinations, WSRS, BAWS, BARS and BAWSRS with ratios of 1.5 and 2.5 is shown in figure 1. The startup phase of methane production was slow for BAWS, RSBA and BAWSRS, observed for both ratios while WSRS combination for both ratios started producing methane with concentration of 17% and 41% for ratios 2.5 and 1.5 respectively on fourth day after experiment was established. Other combinations of ratio 1.5 BAWSRS and BAWS produces biomethane 29%, 37% on seventh and eleventh day of experiment establishment. For the combinations of ratio 2.5 BAWSRS and BAWS has shown the increase in biomethane production on seventh and 20th day of experimentation of 11% and 3%. The combination of RSBA has produced the lowest biomethane among all combinations of ratio 2.5 and for ratio 1.5 in the start the production was slow but increased gradually with time.

The stabilization phase for all combinations (ratio 1.5) was started after 11th day when experiment was established. Maximum methane produced by WSRS, BAWS, BARS, BAWSRS (ratio 1.5) was 70.63% ,64.5% ,65%, 69% respectively. Similarly, stabilization phase for all combinations (ratio 2.5) was observed after 20th day, maximum methane production rate for WSRS, BAWS, BAWSRS and BARS (ratio 2.5) 68.5%, 58%, 65.5% and 18% respectively. The methane production concentration for both ratios were adjacent, but the time required by the combinations to approach maximum production rate was different.

It has been observed that during startup phase three combinations BAWS, BARS and BAWSRS of both ratios has long startup when compared with the WSRS. During startup phase the methane production is slow because of already trapped oxygen in the digester which limits the anaerobic bacteria to start anaerobic digestion process. The anaerobic bacteria are activated after some time when digestion is started, and the facultative situation ends. [1]

The cumulative methane yield mentioned in figure 2 for both ratios was calculated at standard temperature and pressure. The maximum methane yields obtained from all combinations (ratio 1.5) WSRS, BAWS, BARS and BAWSRS were 3494.409 mlCH_4/gVS, 2496.298 mlCH_4/gVS, 2826.252 mlCH_4/gVS and 2826.926 mlCH_4/gVS respectively whereas for ratio 2.5 methane yield obtained for all combinations WSRS, BAWS, BARS and BAWSRS were 2798.950 $mlCH_4$/gVS, 1291.847 $mlCH_4$/gVS, 551.822 $mlCH_4$/gVS and 2089.752 $mlCH_4$/gVS respectively. It can be clearly figured out from the figure 1 and figure 2 that ratio 1.5 had greater potential as compared to ratio 2.5. In the present study wheat straw, rice straw and bagasse are agricultural residues and agricultural or lignocellulosic waste has complex structure and lignin is most difficult to be degraded, presence of high lignin content and cellulosic crystallinity is reduced by pretreating the substrate, the treatment could be mechanical, chemical, biological, thermal. These pretreatments reduce the lignin content and the cellulosic crystallinity to increase digestibility. [2] Lignin has the recalcitrant structure that limits degradation of lignocellulosic waste whereas cellulose and hemicellulose degrade after hydrolysis process, this degradation of cellulose and hemicellulose of lignocellulosic waste would result in biogas production. [1][3] Untreated lignocellulosic waste does not have the potential to produce excess biomethane yield whereas the pretreatment enhances the biomethane yield,[4] [5] . It has been observed that combinations of BAWS, BAWSRS and BARS has the prolonged startup phase and the less methane yield when compared with the combination of WSRS for both ratios the combinations having bagasse in them and among all three substrates bagasse has the highest lignin content [6] which is difficult to degrade lignin is the cell wall of the lignocellulosic material which provides the support to the material and resist microbial attack and oxidative stress, lignin is insoluble in water and therefore anaerobic bacteria require more time to adhere on the substrate to start the anaerobic digestion. [7] The combination of BARS has shown the less biomethane production as shown in figure 2 (b) because lignin content of both rice straw and bagasse collectively resist the anaerobic bacteria for longer duration not to adhere on the surface of the particles of BARS combination.

Additionally all combination of ratio 1.5 and 2.5 were given mechanical pretreatment which increase the surface accessible area and reduces the crystallinity. [8] The surface accessible area and crystallinity is corelated, enzymatic hydrolysis is affected it comprises of four steps adsorption of cellulase enzyme form liquid phase onto the surface of cellulose (solid) and then biodegradation of cellulose, lastly desorption of cellulose to liquid phase, direct contact of the cellulosic hydrolysis enzyme with surface area is essential for the hydrolysis.[9] [10] [11] The Delay in the cellulosic enzyme will slower the hydrolysis this was observed for all combinations of ratio 2.5. Ratio 1.5 shows better results when compared with ratio 2.5 although the methane yield of ratio 2.5 provides appropriate methane yield values but the startup phase for the methane

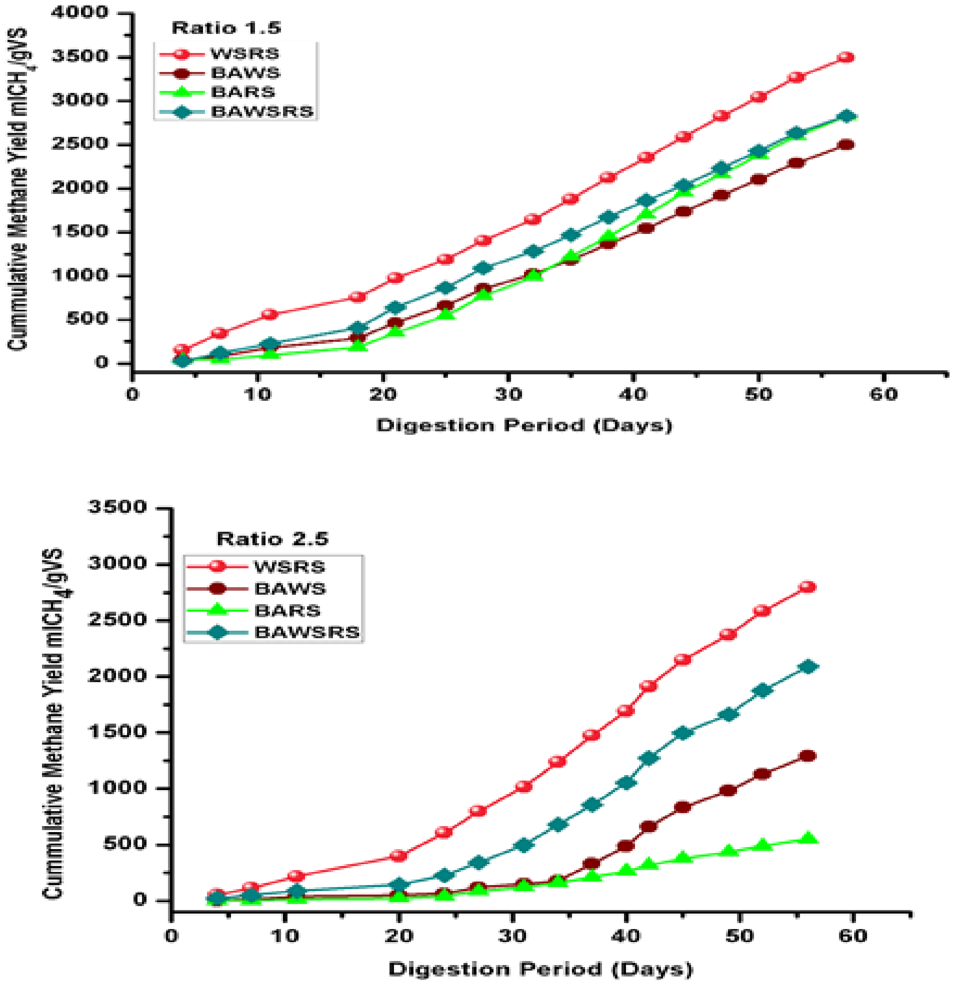

Figure 1 Cumulative Methane Yield at STP for Ratios 1.5 (a) and 2.5 (b)

production was too long because the hydrolysis is very slow, and the degradation of the substrate started late the bacteria required more time for digestibility of substrate i.e. after degrading cellulose and hemicellulose biomethane production was started. The increase in surface accessible area decreases the crystallinity and decreases the surface of polymerization to improve biodegradability these are the factors which fasten the hydrolysis and increase biogas yield [4] which was observed for all combinations of ratio 1.5.

4.2 pH and Volatile Solids Reduction

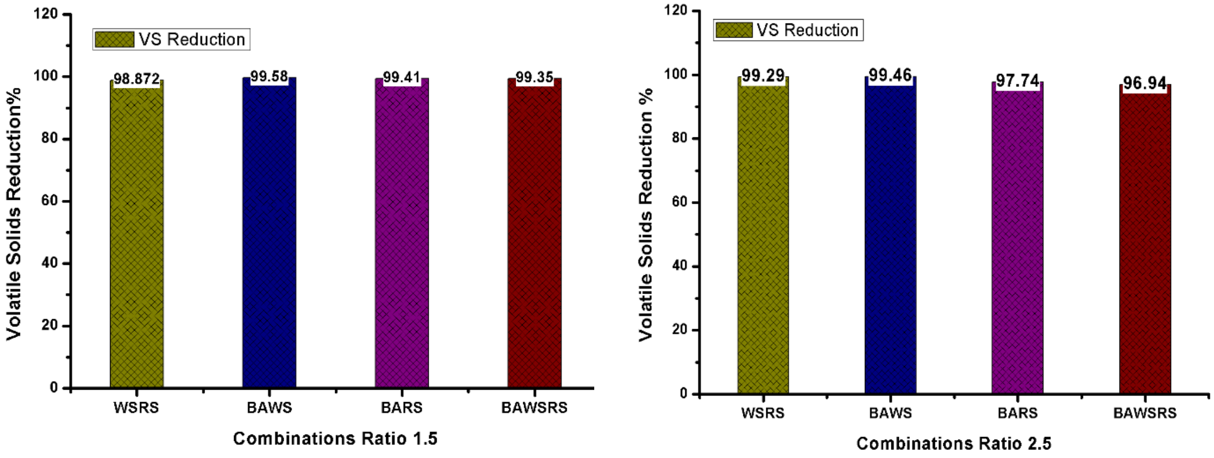

Figure 4.3 **Volatile Solids Reduction of all Combinations Ratios 1.5 and 2.5**

4.2.1 Volatile Solids Reduction

Production of Biogas is correlated with the degradation or digestibility of the organic matter by anaerobic microorganisms. VS reduction is the amount of VS degraded by the bacteria, higher degradation leads to more VS reduction yields excessive biogas production.[9] Additionally, the VS degradation depends on the activity and adaptability of inoculum towards substrate in anaerobic system. [10]

The VS reduction in this study was calculated by using the formula in equation 1 [11]

$$\text{VS reduction \%} = 1 - \left[\frac{\text{VS digestate} * (100 - \text{VS feed})}{\text{VS feed} * (100 - \text{VS digestate})} \right] * 100 \quad \text{---------equation 1}$$

The VS reduction calculated for this study is shown in figure 3 for all combinations and ratios of 1.5 and 2.5. Similar rate of VS reduction has been investigated for all combinations when the experiment was ended though substrates were still producing the maximum rate of biogas. The value of VS reduction ranges from 96.94 % – 99.58 %, these VS reduction values shows that anaerobic bacteria degraded the substrates to the maximum and that the maximum digestibility of the substrates was observed and after few days there is a possibility of reduction in biogas production due to maximum digestibility of the substrates. The higher values of VS reduction illustrates the maximum utilization of carbon content present in the substrates which is responsible for biogas production. [10]

4.2.2 pH

Figure 4 shows the pH values of the reactors after digestion, it can be observed that all reactors are having optimum pH value ranges from 6.95 -7.8 except the combination of BARS having pH of 5.5. The methanogenic bacteria are active at the pH of 6.5-8.5 and yields maximum biogas. [12] [13] pH values of reactors show that methanogenic

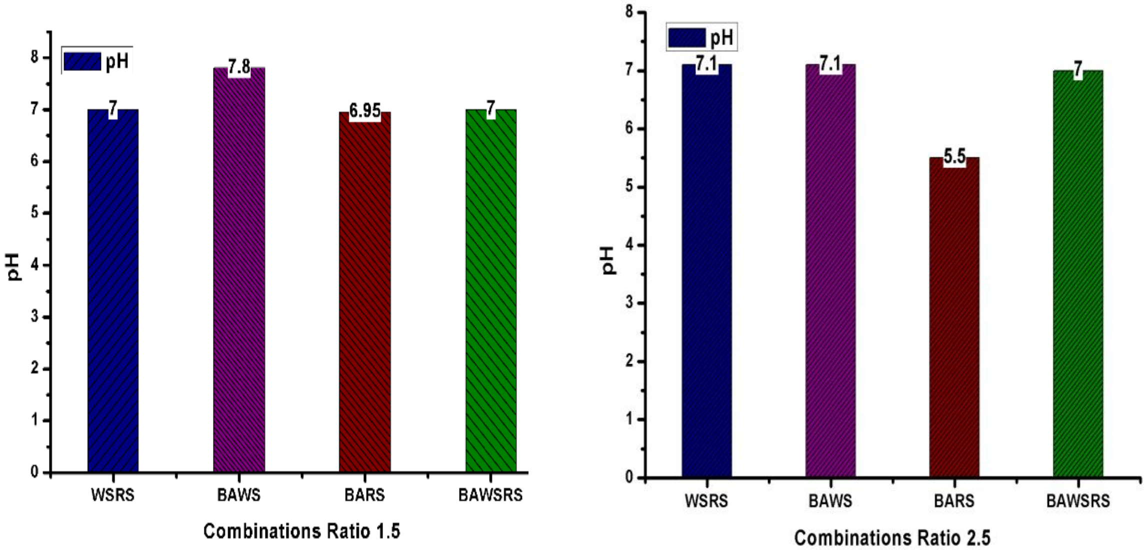

Figure 4.4*:* **pH of all combinations Ratios 1.5 and 2.5**

bacteria produced biogas but for the BARS the methanogens were not active and so that combination yields lower methane production among all other combinations of both ratios 1.5 and 2.5

4.3 Kinetic Model of Biogas Production

4.3.1 Modified Gompertz Model

The modified Gompertz model was applied and the model depicts the cell density during bacterial growth periods in terms of exponential growth rate and lag phase interval. An assumption of methane production rate in a batch digester corresponding to the specific growth rate of methanogenic bacteria led to Equation 2.

$$\mathrm{G(t)} = \mathrm{G}^{\circ} exp\{-exp[Rmax.e/G^{\circ}(\lambda - t) + 1]\} \quad \text{------------ Equation 2}$$

$G(t)$ = cumulative methane yield at digestion time (t) (LCH_4/gVS)
G° = methane potential of the substrate (L/gVS)
Rmax = maximum methane production rate (L/g VS. d),
k = lag phase (day)
t = time (day)
e = exp (1) = 2.7183

The lag phase depicts the minimum time required by the bacteria to acclimatize in the environment or minimum time taken for biogas production. The maximum methane production rate (Rm) describes specific growth rate of methanogenic bacteria. Higher value of Rm results in more methane production. [14]

This nonlinear regression model was used to adjust the measured methane yield values with the predicted methane yield values. The nonlinear regression analysis was performed using IBM SPSS statistics 22.0. calculated the Rm, lag phase and predicted methane yield.

Table 1 summarizes the Gompertz model results and the Graphs in figure 3 and 4 shows the relation between the predicted and measured methane yield for all combinations of ratios 1.5 and ratio 2.5 respectively. The Modified Gompertz model illustrates that in

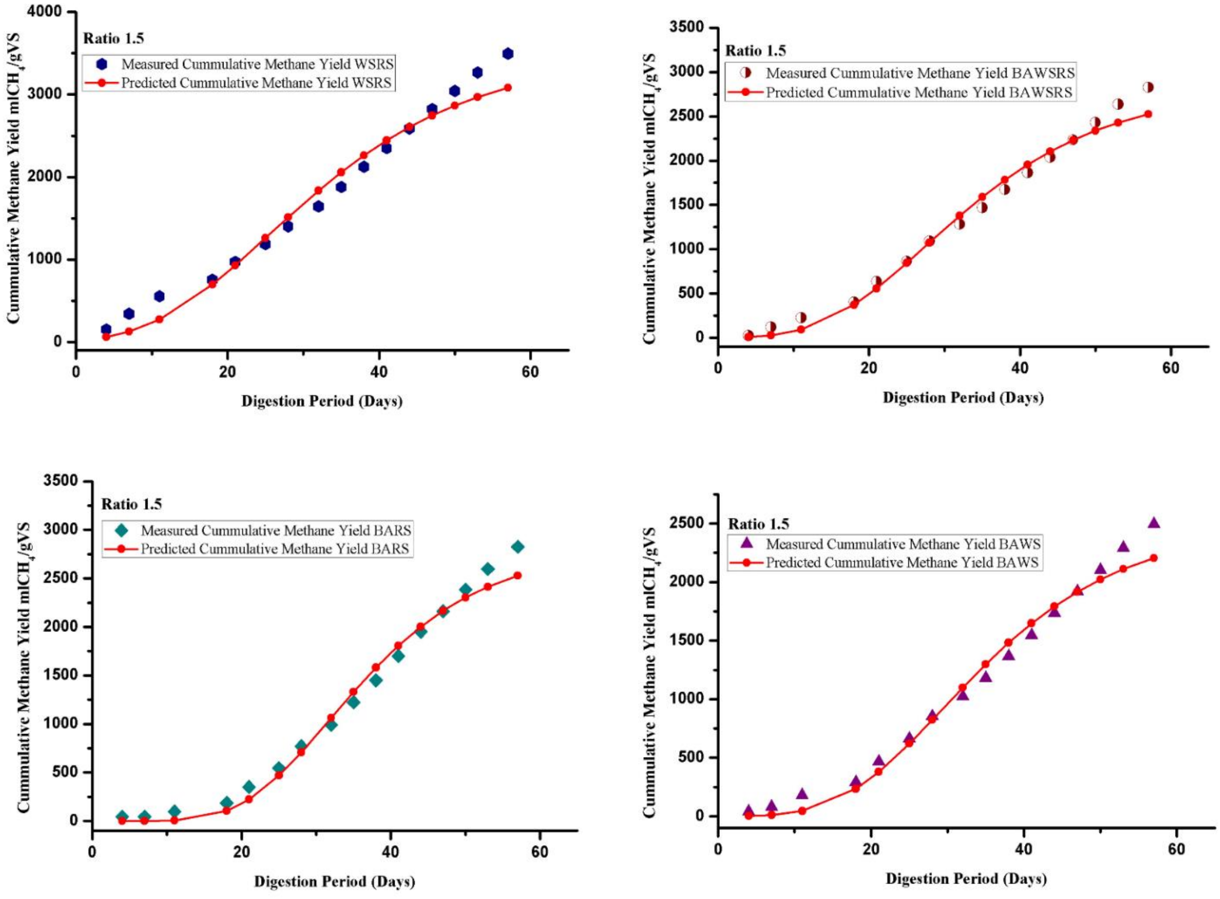

Figure 4.5: Relationship between Measured and Predicted Cumulative Methane Yield using Modified Gompertz Model

ratio 1.5 the combination of WSRS have the short lag phase and when the lag phase ends log phase or exponential growth rate i.e. increase in degradation rate of substrate has been observed whereas all other combinations have greater lag phase. The combination of BARS has longest lag phase when compared with all other combinations this is because of the higher lignin content and longer hydrolysis phase that the bacteria require longer time to produce methane. Furthermore, in ratio 2.5 combination of WSRS have shorter lag phase and BAWS has the longer lag phase when compared to other combinations. The prolonged lag phase and longer hydrolysis phase is due to higher lignin content and as discussed previously that lignin is difficult to degrade so require longer time for bacteria to reside on substrate and start degrading the material. Additionally, comparing the both ratios 1.5 and 2.5, ratio 2.5 combinations has longer lag phase, and this is because of prolonged hydrolysis phase in anaerobic Codigestion the methanogenic bacteria took a little longer to produce excessive biomethane. The Modified Gompertz model was observed as the better fit for our study as the difference between the predicted methane yield mlCH4/gVS and measured methane yield mlCH$_4$/gVS was nearby or less than 10% and the coefficient of Regression ranges from (0.970 - 0.975) [15][14][16][17]

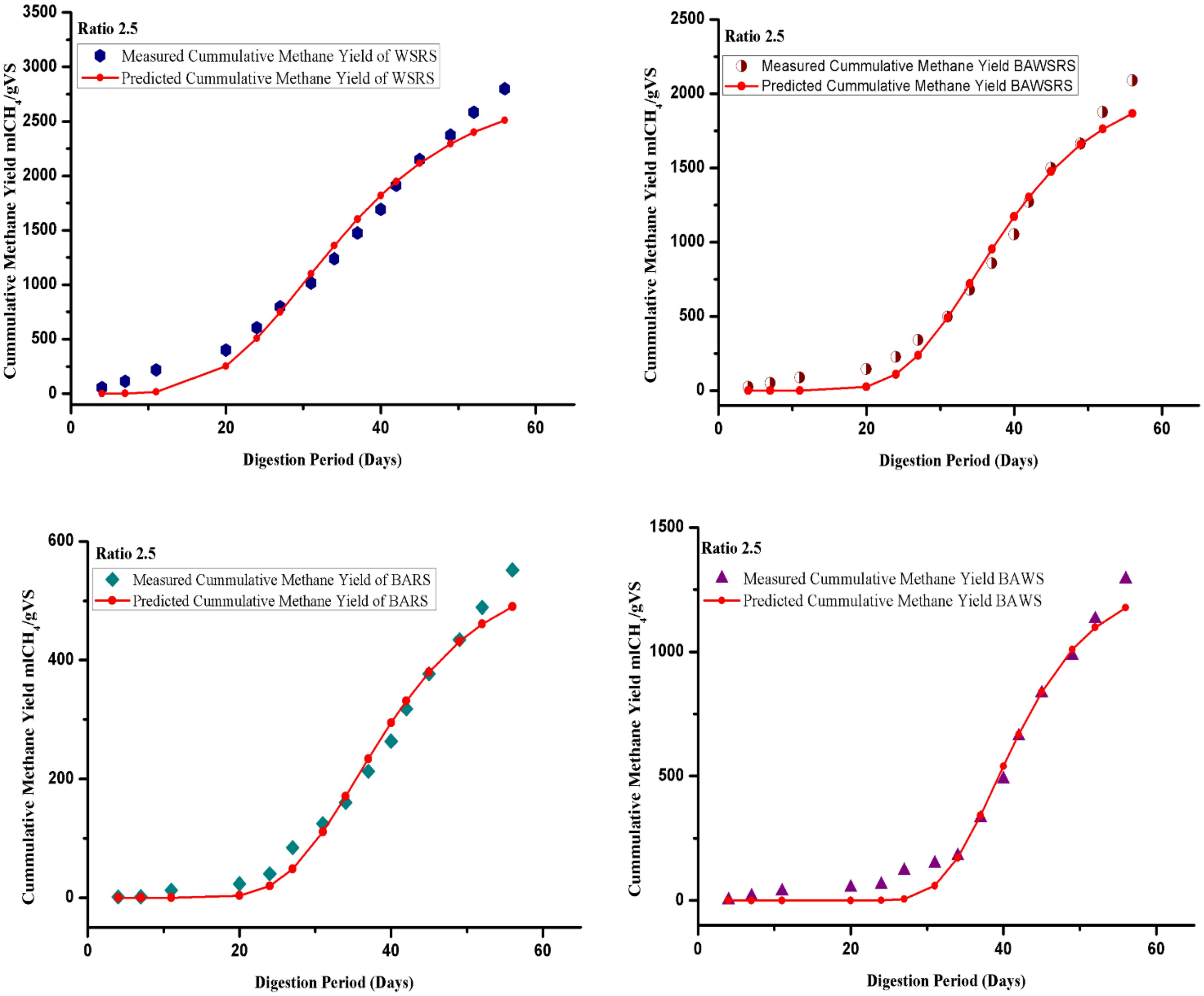

Figure 4.6 : Relationship between Measured and Predicted Cumulative Methane Yield using Modified Gompertz Model

Table 4.1 Parameters corresponding to representation of Cumulative Methane Yield using Modified Gompertz Equation

Parameters	**Combinations Ratio 1.5**				**Combinations Ratio 2.5**			
	WSRS	**BAWS**	**BARS**	**BAWSRS**	**WSRS**	**BAWS**	**BARS**	**BAWSRS**
R^2	0.968	0.979	0.984	0.983	0.978	0.983	0.983	0.980
λ (days)	10.016	16.151	20.234	14.033	18.585	31.886	25.9218	24.80
Rm $mlCH_4/VS.d$	5.744	4.321	6.236	4.824	5.886	3.918	0.360	5.238
Methane Yield Predicted mlCH4/gVS	3082.69	2205.60	2528.11	2524.52	2510.25	1177.4008	490.11	1865.78
Measured mlCH4/gVS	3494.40	2496.29	2826.25	2826.92	2798.95	1291.8471	551.822	2089.75
Difference %	12.5	21.39	11.13	11.30	10.87	9.2	11.84	11.32

4.4 Design of Small Scale Biogas Digesters for Rural Community

Rural communities are energy deficient but had a lot of lignocellulosic waste which could be used as the raw materials and had great potential for biomethane production. Before proposing any design of the digester selection of the material and potential of the feed to be fed in the was determined by using biomethane potential tests. BMP tests determine best combination with best feed to inoculum ratio which had the potential for maximum biomethane production. From the detailed study carried out it has been observed that WSRS combination of ratio 1.5 had the potential for generation of maximum biomethane and the production was started earlier at the 4th day after commencement of experimentation. Figure 7 shows the schematics of the proposed small-scale biogas design for rural community and operation of the system is mentioned below.

4.4.1 Design and Operation of Proposed System

The system consists of a volume 3 m^3 stainless steel digester tank with a working

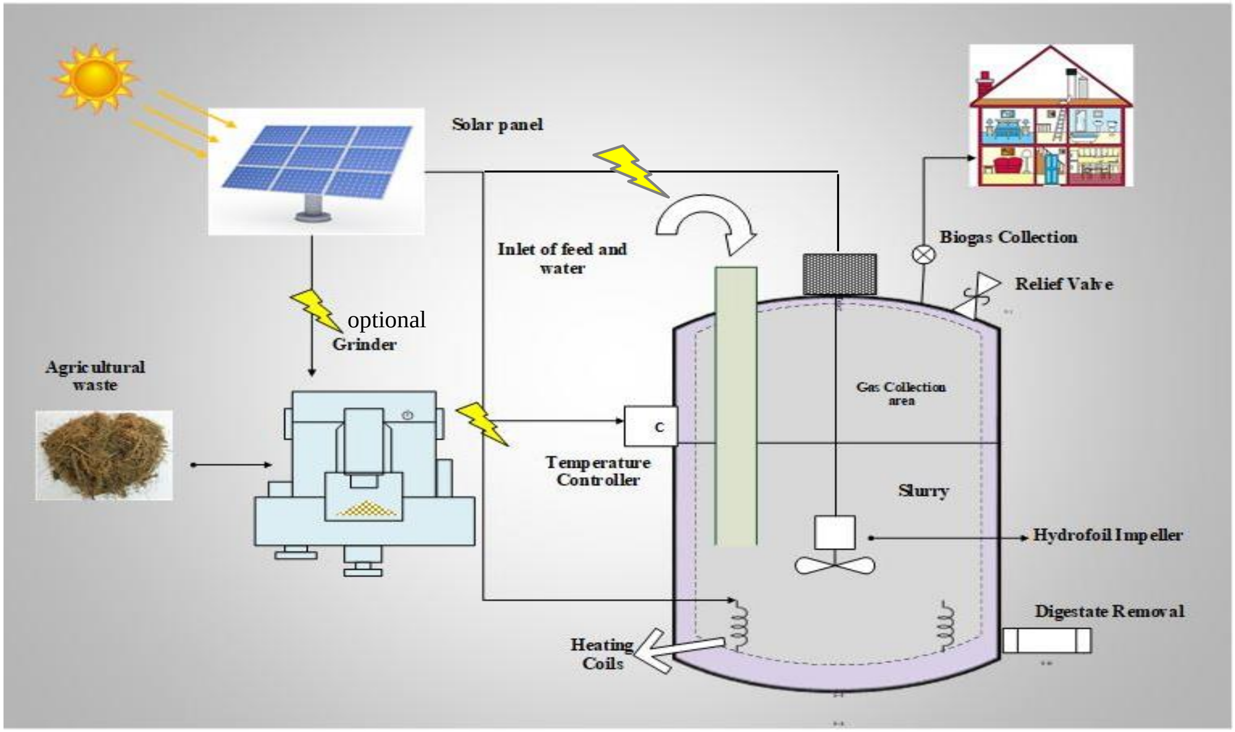

Figure 4.7: **Proposed Design of Small Scale Biogas Digesters for Rural Community**

volume of 2.1 m^3. Digester will be semi continuous biogas digester operated at the mesophilic conditions.

Lignocellulosic waste (combination of WSRS) was finely grinded by using grinder and reduced the waste to the particle size of 1-3mm. The substrate from the grinder was added into the digester and the inoculum which is the source of methanogenic bacteria was collected and added manually into the digester. Mixing of the substrate and inoculum is essential in anaerobic digestion process hydrofoil impellers are suggested for the mixing, hydrofoil impellers has better suspension ability usually marked as the standard and it consumes low power. The impeller would not mix the substrate throughout the day, this would be done timely hydrofoil impeller would be connected to the Variable frequency drives that conserve the energy. Digester would be filled up to 70% of its total volume and rest 30% would be left for the biogas storage. For the winter season when the external temperature is very low which is an important parameter in anaerobic digestion would slow or stop the process, to overcome this problem heating coils are attached at the end of the digester heating coils would be connected with the temperature controller that controls the temperature to maintain the mesophilic conditions of 35°C for maximum production of biomethane. The solar panel connected would be the source of electrical energy for the grinder, temperature controller, heating coils and impeller present in the digester for the dark days the battery is attached with the solar system. Biogas would be stored in the gas cylinders; the gas would be enough for the load of one house having 6 – 8 family members.

4.4.2 Improvement in the Proposed Biogas system in comparison with Conventional Biogas digesters installed in developing Countries

Already installed biogas plants in the developing countries like fixed dome biogas digesters, floating drum biogas digesters and plug flow biogas digesters were not performing upto mark the success rate was quiet low the reasons towards the failures includes technical, social and economic problems.

Biogas plants already installed in the developing countries mostly includes fixed dome, floating drum and tubular or plug flow digesters, these biogas plants have high installation and maintenance cost and failures in these biogas plants have been observed the most common problem is the leakage of the gas (methane) from the spaces left during the construction, and the leakage in the piping system has also been observed just because of the unprofessional connections, the pipes are not fixed properly.[18] Problems other than leakage include corrosion in the mild steel tank which reduces the life span of the material and increases the maintenance cost. [19]The material selected for the suggested biogas plant is stainless steel grade 314 because of its corrosion resistant property and have a life span of more than 30 years which reduces the maintenance cost of the biogas digester.

These designs of biogas plants lack agitation or mixing which results in the improper mixing of nutrients, increase in the organic solids in the bottom of the digester and removal of the accumulated solids from the bottom of the digester is necessary as it increases the volume of the substrate which results in the reduction of the gas collection portion [20] to avoid such issues, the proposed biogas plant has the hydrofoil impeller for proper mixing.

Already developed biogas plants lack the temperature control. In the Anaerobic digestion process temperature plays a very important role low temperature would result in low biogas production so the temperature should be maintaining the mesophilic conditions for better biogas production.[21] To overcome this problem the proposed system has the temperature controller.

In colder regions or when there is change in weather conditions the biogas production rate decreases because of decrease in temperature the methanogenic bacteria stop performing biogas due to inappropriate operating conditions, [20] an addition of heating coils in the system is to retain the temperature in colder climate and for the constant production of biogas. Oversizing of the biogas digester and addition of low organic load comparing the total volume is also a reason of low biogas production. [22] The proposed system has calculated organic loading rate according to the substrate and volume of the digester for maximum biogas production. The proposed system reduces GHG to 0.2 tCO_2 when compared with the natural gas.

4.5 Economic Analysis

Economics analysis was performed on RetScreen 4.0. Method 1 was applied for calculating the cost benefit ratio of the proposed system. Biomass system is used for heating of the house following parameters were considered. The Economic analysis shows that the model is financially suitable having the payback period of 1.9 years and a life span of 25 years. The emission analysis shows that the project reduces the CO_2 emissions as the base case produces 2.1 tCO_2 and the propose case produces 0.1 tCO_2 emissions which results in 2.0 tCO2 emission reduction per year.

Table 4.2: Heating System

Parameters	Units	Base Case	Proposed Case
Heated floor area for building	**m^2**	121	121
Energy efficiency measures	**%**		10
Heating load for building	**W/m2**	37	33
Domestic hot water heating base system	**%**	50	50
Total Heating	**MWh**	8	7

Table 4.3: Base Load Heating System

Parameters	units	Base Case	Proposed Case
Technology			
Capacity	kW	4.5	4.5
Heating Delivered	MWh	7.8	7.0
Fuel Type		Natural Gas m3	Biomass
Seasonal Efficiency	%	65	80
Fuel consumption – annual	m^3	1,153	2
Fuel rate	Rs / m^3	26.520	11.050
Fuel Cost	Rs	30,569	18

Table 4.4: Peak Load Heating System

Parameters	**units**	**Base Case**	
Technology			
Suggested Capacity	kW	1.8	
Capacity	kW	4.5	111.1 %
Fuel Type		Natural gas m3	
Seasonal Efficiency	%	65	
Fuel consumption – annual	m^3	51	
Heating Delivered	MWh	0.3	4.9 %

Table 4.5: Emission Analysis

GHG emissions	**Units**	**Values**
Base Case	tCO2	2.1
Proposed Case	tCO2	0.1
Gross annual GHG emission reduction	tCO2	2.0
Net annual GHG emission reduction	tCO2	2.0

4.5.1 Financial Analysis

The life of the project, payback period is shown in the graph mentioned below and exact values are mentioned in table 6

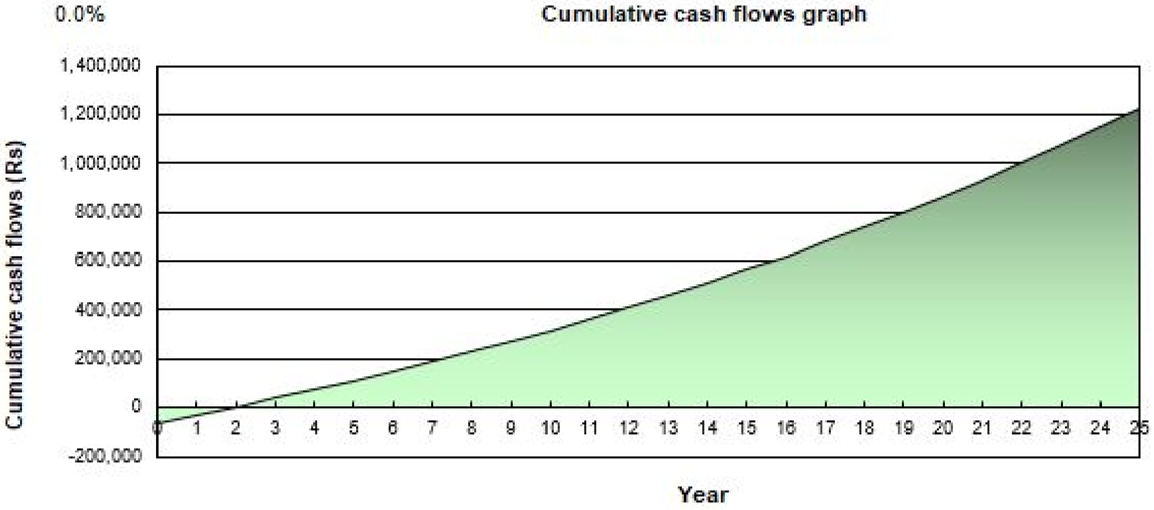

Figure 4.3 Cumulative Cash Flow Graph

Table 4.6: Financial Parameter and financial Viability

Financial Parameters	Units	Values
Inflation rate	**%**	3.8
Project life	**Years**	25
Total Cost	**Rs**	60,000
Financial Viability		
Simple payback	**Years**	2.0
Equity payback	**years**	1.9

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Chapter # 05

Conclusions & Recommendations

The following conclusions and recommendations were extracted from the current study compiled in this thesis.

5.1 Conclusions

Biogas technology is sustainable source of energy production that benefits people to reuse the industrial, agricultural and municipal waste. Anaerobic biogas digesters are developed previously and used by the rural community using cow manure as the feed. The present study proposed the design of anaerobic digesters assisted with solar panels using crop residues and cow manure as a feed. Rural community are rich with crop residues and cow manure using these resources as a feed of anaerobic digester for biomethane production. Biomethane potential of three selected substrates (wheat straw, rice straw and bagasse) were analyzed by Codigestion of lignocellulosic waste and cow manure using biomethane potential setup. It has been investigated that among four combinations of both ratios 1.5 and 2.5 combination WSRS has shown the highest biomethane production and considering the best ratio for biomethane production WSRS with ratio 1.5 has shown the best results so far. WSRS with proportions of ratio 1.5 would be used as a feed in the proposed anaerobic digester. Proposed design of anaerobic digester minimizes the risks and failures of the already developed biogas digesters, more efficient could be used in all climatic conditions is simple, easy to operate with improved robustness and cost-effective system as well as a sustainable system fulfilling all energy needs from renewable energy resources to provide rural community a better living.

5.2 Future Recommendations

- Fabrication, Operation and testing of Biogas Digester at Mesophilic condition
- Life cycle assessment (LCA) of the proposed small scale solar panel assisted biogas digester
- Strategic planning for dissemination of anaerobic digester systems in rural community give awareness to people for better usage of natural resources despite of wasting them.
- Investigation of biomethane production by using Anaerobic Codigestion of lignocellulosic waste with feed to inoculum ratios of 3.0, 3.5 4.0 and 4.5

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Annexure 1

Co-digestion and optimization of lignocellulosic residues for biomethane production in Anaerobic digestion

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ABSTRACT:

Rural communities in developing countries run a major energy deficit and are consequently in need of cost effective technological solutions. Opportunistically, agricultural waste is abundant in the rural areas which can be used as a source for Biomethane production. This study focuses on evaluation and the effectiveness of anaerobic co-digestion for three types of the lignocellulosic material. The selection of lignocellulosic material Wheat Straw (WS), Rice Straw (RS) and Bagasse (BA) is based on the potential bioenergy and abundant availability of crops reported in the Biomass Atlas of Pakistan. Therefore, biochemical methane potential (BMP) test was constituted for the conversion of lignocellulosic materials into biogas. The effect of feed to inoculum (F/I) ratio with diverse co-digestion ratios of 1.5 and 2.5 was observed for 60 Days at mesophilic conditions for the combinations of wheat straw and rice straw (WSRS), rice straw and bagasse (RSBA), Bagasse and wheat straw (BAWS) and bagasse, wheat straw and rice straw (BAWSRS). The physical and chemical parameters of all three substrates and inoculum were examined. A significant increase in biomethane production (70%) was achieved by WSRS at F/I ratios of 1.5. The optimized combination of the lignocellulosic material developed in this study would lead to efficient production of bio-methane, thus contributing towards meeting the energy needs of rural communities.

Key words:

Lignocellulosic, co-digestion, Biomethane, Biomass atlas, Gas Chromatograph (GC).

1. INTRODUCTION:

1.1 Anaerobic digestion of biomass

Anaerobic digestion is cost-effective bioenergy conversion technology adopted globally. It’s a biological process in which organic waste, agricultural residues and industrial wastes are decomposed by microorganisms in the absence of oxygen and produces biogas, 50-75% CH_4, 20-25% CO_2 and traces of nitrogen(N_2), hydrogen sulphide (H_2S), hydrogen(H_2), carbon monoxide (CO). Biogas produced could be used in multiple ways as a source of heat, electricity production, internal combustion generators, micro-turbines and fuel cells. Biomethane produced through anaerobic digestion is distributed into four processes hydrolysis, acidogenesis, acetogenesis and methanogenesis.[1]

1.2 Lignocellulosic Materials

The lignocellulosic biomass wheat straw, rice husk, sugarcane bagasse rice straw, corn Stover etc. are vastly available around the world. Methane production from lignocellulosic material is rare because they are arduous to digest, Lignocellulosic material is composed of three types of polymers lignin, cellulose and hemicellulose.

Lignin is the major component of the plant cell wall and it endow the structural support, impermeability and resists the microbial attack and is recalcitrant to digest by microbes for renewable biochemical conversion. It is non- soluble in water. Cellulose is rate limiting substrate and is hard to degrade, structure of cellulose could be defined or it might not have the proper structure. Cellulose has fibrils that are hard to digest by microorganisms. [2] Hemicellulose is also very rigid to digest it acts as a linkage between cellulose and lignin. Hemicellulose have low digestibility and passes undigested through the anaerobic digestion processes. [3] Lignocellulosic materials have complex and rigid structure and requires long time for degradation, the selection and use of appropriate pretreatment method will shorten the time of degradation and overcome the limiting step of substrate hydrolysis by enhancing the enzymatic degradability of lignocellulosic biomass and by increasing the biogas yield. In addition, Pretreatment methods are divide into various methods physical, biological, mechanical, enzymatic, chemical pretreatments.[4] Physical pretreatment reduces the particle size of lignocellulosic material which results in improvement of handling and treatment of biomass. The reduction in the size of the biomass would modify biomass structural properties and increases the surface area reduces the degree of cellulose crystallinity, and decrease the degree of cellulose polymerization for improved digestibility.[5]

1.3 Anaerobic Co-digestion

Anaerobic co-digestion refers to anaerobic digestion process which is used for the treatment of the multiple substrates for the generation of biomethane. [6][7]The steps involved for generation of biomethane are identical to anaerobic digestion. Moreover, methane production strongly depends on the numerous factors like pH, carbon to nitrogen ratio, temperature, nutrient content, particle size, carbon to phosphorus ratio. If the proper conditions are deranged it will drops the performance and would results in failure of the process.[7] Imbalanced nutrient in anaerobic digestion is the limitation of the process therefore to balance the nutrient ratio the anaerobic co-digestion process is implemented.[8] Anaerobic Co-digestion technology provides the opportunity to balance the nutrients and improves the production. C/N ratio is an important indicator for controlling the biological treatment systems. High C/N ratio shows the rapid Nitrogen accumulation by methanogens which effects the nutrients deficiency and results in lower methane production. In lignocellulosic material the residues containing the low level of nitrogen have high C/N could be mixed with the high level of nitrogen have low level of C/N to balance the nutrients. The imbalance in the ratio would causes the accumulation of the VFA's of ammonia inhibition.[9] The optimal C/N ratio is 15-35, 25 is commonly used, decrease in C/N ratio would be because of inadequate environmental conditions, temperature, pH variation and free ammonia inhibition the decrease in operating temperature. [10] The presence of low C/N ratio would result in accumulation of ammonia and excess amount of ammonia will increase the pH if pH exceeds 8.5 it will show the toxic effect on methanogenic microorganisms. It has been investigated that among bio-ethanol production and methane generation from the lignocellulosic material is more economical and environmentally beneficial way of utilizing biomass.[11]

2. MATERIALS AND METHODS

2.1 Raw material

Selection of material was based on Biomass atlas Pakistan, the selected agricultural waste had high theoretical potential and farmer was willing to sale the raw material.[12]

Wheat straw, rice straw and bagasse were collected from the local areas of Punjab Pakistan. Prior to use the samples were mechanically pretreated firstly reduced to the size of 5 inch by using scissors and then grinded by means of grinder decreasing the particle size to 2-7 mm. Inoculum was collected from the anaerobic digester installed in the rural areas of Pakistan.

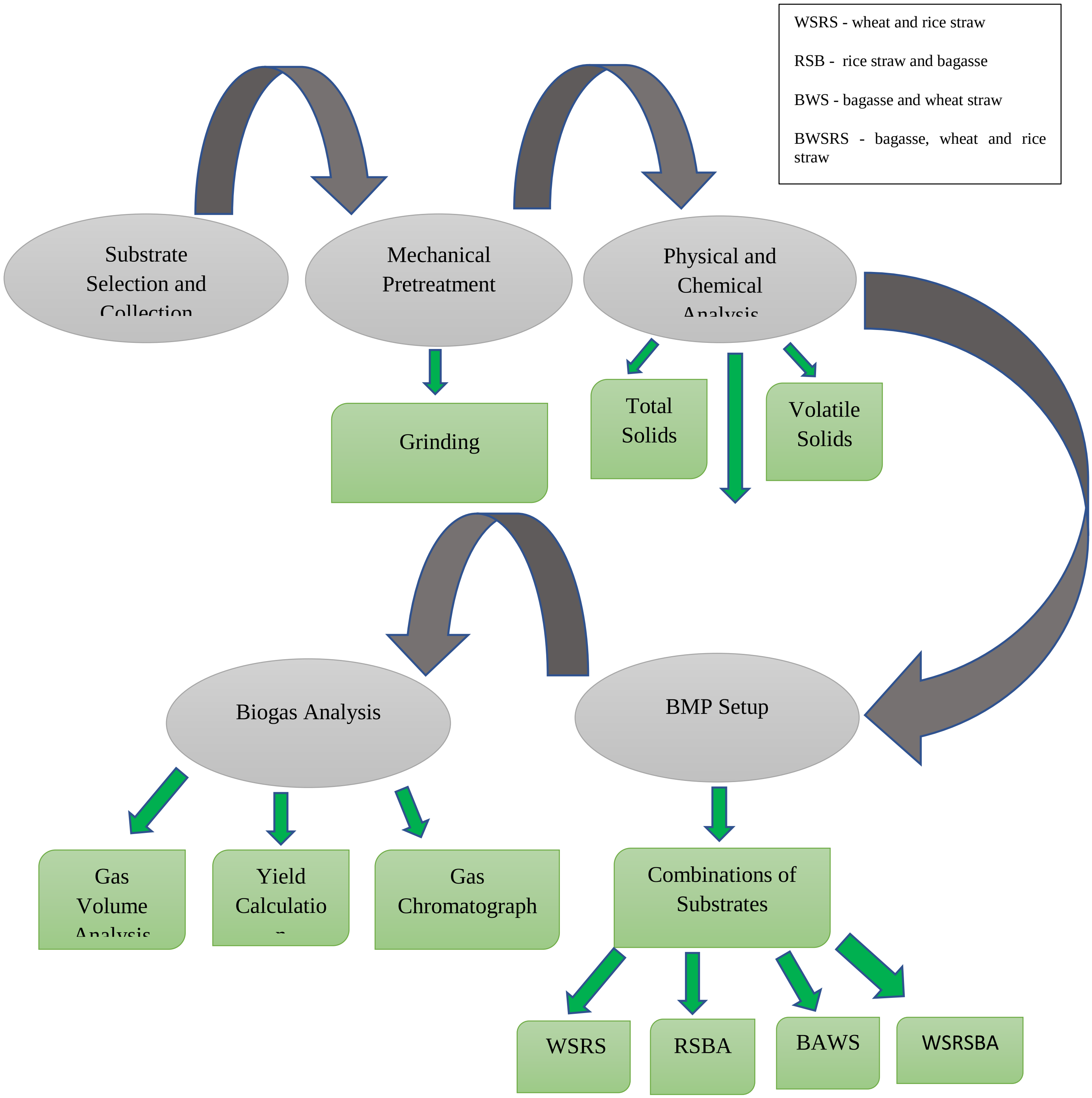

Figure 4 Framework of the BMP Setup

2.2 Anaerobic Digestion Experimental Setup

Methane production analysis of all substrates with possible combinations at different ratios was carried out. The combinations were RSWS, WSBA, BRS, BAWSRS with ratios of 1.5,2.5. Mesophilic conditions 30-35°C were provided to run the experiment. For experimentation the Biochemical methane potential setup was established shown in figure 2.[13] Experiment was conducted in 300ml bottle and 210ml was considered as the working volume for each ratio. The substrate along with inoculum and water was added and to create anaerobic conditions purging of nitrogen was carried out for 5 min while rubber stoppers were used to seal the mouth. Syringes of 25ml were inserted in the sealed bottles for collection of biogas. Addition of Inoculum and water in a bottle worked as Control for every ratio. Analysis of Methane production was started after 5 days' digestion. All the bottles were agitated manually every day and were incubated at 30-35°C.

3. ANALYTICAL METHODS

3.1 Characterization:

3.1.1 Physiochemical Characterization:

The initial and final values of total solids (TS%) and volatile solids (VS%) were analyzed using the APHA standard method. pH is one of the key factor and it was monitored because the methanogens growth could be influenced by the pH level. pH was measured with the Hannah pH meter. The elemental analysis of all substrates was conducted by the SEM/EDS.

3.1.2 Gas Chromatography:

Methane produced by the anaerobic digestion of the agricultural waste was analyzed from the Gas chromatograph 2010 plus (Shimadzu) having column of RT-MS5A (TCD) and column maximum temperature was 300°C, temperature equilibrium time was 3 min starting from 35°C (2min). Methane yield was analyzed by the difference amount of methane produced from the substrates and average production from the control to the mass of volatile solids in substrates fed into the digester.

Table 4 Chemical characteristics of substrates

Substrate	**Total Solids (TS) %**	**Volatile solids (VS) %**	**C%**	**N %**	**H %**	**O%**	**C/N**
Wheat Straw	99	83.33	52.21	9.79	5.90	33.94	5.33
Rice Straw	98.5	62.42	19.34	3.36	6.1	59.6	5.7
Bagasse	98	80	13.6	0.36	5.38	33.11	37.778

4. RESULTS AND DISCUSSIONS

The methane production of both ratios was observed periodically during the 60 days of experimentation. The methane production from both ratios distributed in three phases, adaptation phase, first phase of stabilization and then second phase of stabilization. The adaptation phase of combination BAWSRS, BAWS and RSBA continued for 7 days and methane produced was 29%,14%, 9% respectively, later the first stabilization phase occurred prior to 23rd day with the production of 69%,65% and 47.63% from 25th day till the 60th day of analysis the second phase of stabilization was observed along with the production of 58.513%, 68.292% and 66.177%. Hydrolysis is the limiting step for the combination of RSBA, as hydrolysis is the limiting step indicates that microbes cannot attack the lignocellulosic structure to degrade the layer and produce biogas from this combination.

RSWS combination of ratio 1.5 have the smallest adaptation phase of 3 days, the first phase of stabilization was started earlier on the 4th day with the methane production of 42.6% and this stage continued till 28th day of the experiment resulting in the production of 62.043%. The second stage of stabilization was started from the 32nd day giving the production of 70.694 which is the maximum value achieved by this combination. The degradation starts earlier, methane production would increase because the hydrolysis occurs immediately, and the amount of nutrients is balanced. Correspondingly the Combinations of ratio 2.5 were also analyzed periodically for 60 days. The combinations of WSRS and BAWSRS have the startup phase until 11th day of the experiment resulting in the production of 30.08% and 11.437%. First phase of stabilization was started from the 20th day to 31st day giving the methane production of 55.916% and 34.606%. The second phase of stabilization ended at 62.233% and 65.509%.

The combinations of RSBA and BAWS limits the hydrolysis step and lowers the methane production and the methanogenic bacteria started producing methane on the 37th day of the experiment giving the production of 51.206 % and 48.407%.

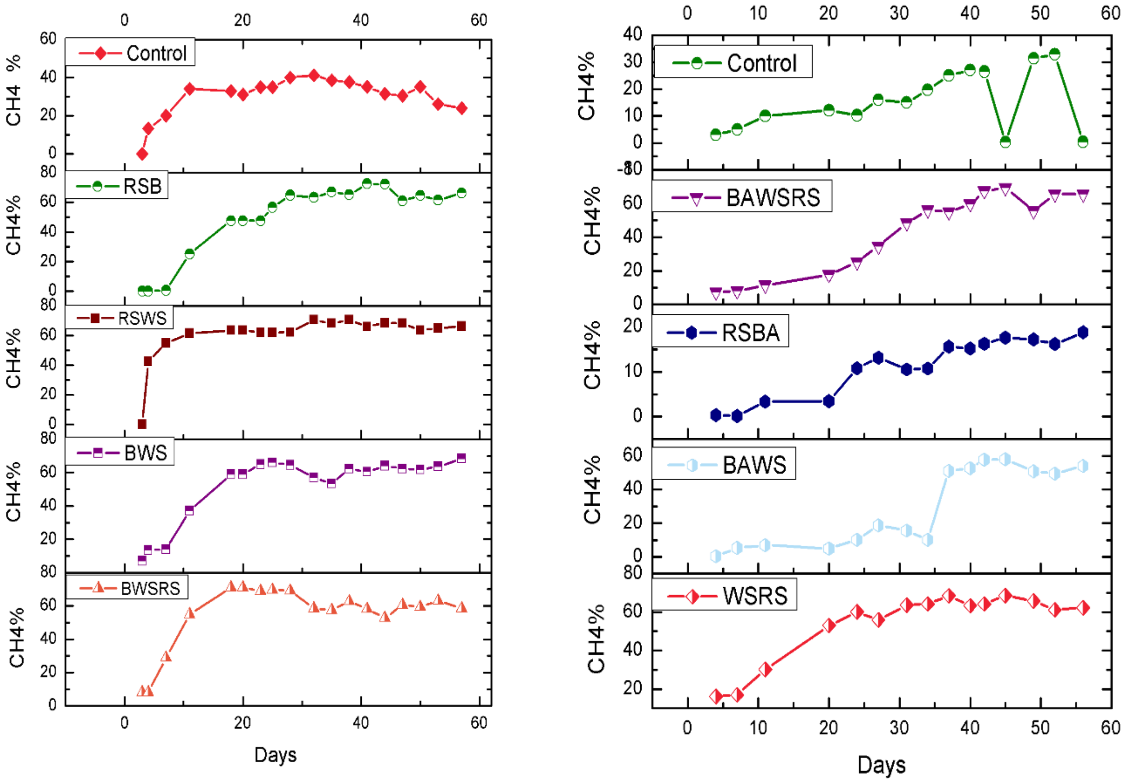

Figure 5 Methane production of all combinations and ratios 1.5 and 2.5

5. CONCLUSION

Lignocellulosic materials are arduous to digest, mono digestion of these substrates would not provide better results therefore the anaerobic co-digestion process is used to increase the biomethane production, anaerobic co-digestion provides the opportunity to balance the nutrients. The methane production would increase if the OLR would be less and temperature would be appropriate. For lignocellulosic material hydrolysis is the rate limiting step that lowers the biomethane production. Lignocellulosic materials are best for the biomethane production rather than bioethanol production.

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