Chapter 5
A Comprehensive Review on the Advancement of Biogas Production Using Leftover Food and Kitchen Waste

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Abstract This review aims to get detailed information about biological reactions in biogas production and the Pressure Swing Adsorption (PSA) approach for biogas upgrading system based on biogas system installed at Rewa Engineering College, Rewa, Madhya Pradesh. The first part of this paper is the pretreatment of microbes, fungal reactions, enzymatic reactions, and metabolic engineering methods. The second part of this paper presents the up-gradation of biogas and their reaction with the PSA technique. The impacts of advancement of biogas production and their potential in advance improving the biogas industry are widely scrutinized. Methane (CH_4) (50–65%) in biogas obtained from biogas digester also consists of ammonia (NH_3), hydrogen (H_2), hydrogen sulfide (H_2S) (1–2%), nitrogen (N_2) and oxygen (O_2) (1–2%), and carbon dioxide (CO_2) (25–40%).

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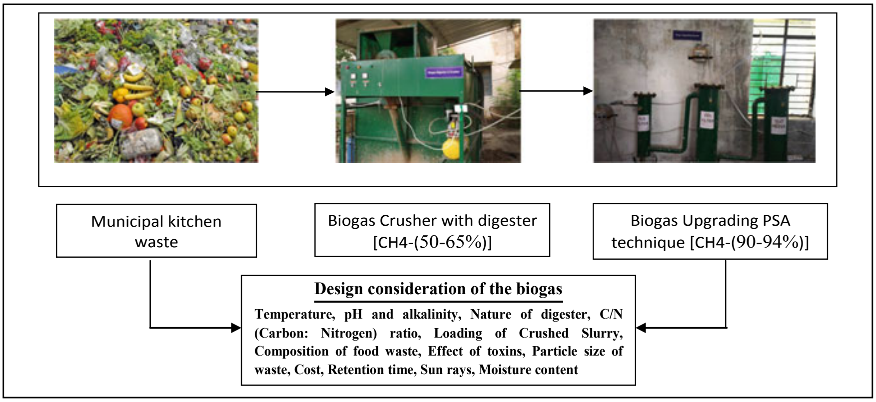
Graphical Abstract



Keywords Biogas anaerobic digestion · Kitchen waste biogas digester design · Biogas chemical reactions · Design consideration

Nomenclature

AD	Anaerobic Digestion
C/N	Carbon: Nitrogen
VFA	Volatile Fatty Acids
PSA	Pressure Swing Adsorption
CH_4	Methane
N_2	Nitrogen
O_2	oxygen
NH_3	Ammonia
H_2S	Hydrogen sulphide
CO_2	Carbon dioxide

5.1 Introduction

Biogas is a sustainable energy source which is the most challenging issue worldwide. Nowadays, lots of renewable and nonrenewable energy sources have been used to fulfil energy demands (Hussain et al. 2019). Biogas is generated mainly from cow dung, buffalo, horse, and other wastes in those days. Kitchen waste can also be utilized to produce biogas due to its high nutritive value (Kumar and Majid 2020). As per the literature, the production ability of biogas using the kitchen is an alternative source with co-digestion of cow manure (Kumar and Tewary 2021). Solid, liquid, or other types of municipality waste are deposited over an open land surface which causes air pollution, human health problems, water pollution, and a totally unbalancing ecosystem (Rawoof et al. 2021).

There are two types of energy sources spread worldwide: controlled energy sources and uncontrolled energy sources. Controlled energy sources can increase productivity, and on the other hand, uncontrolled energy sources can cause problems. By using effective methods or procedures, these uncontrolled sources can be utilized to improve human life. Municipality waste management is also one of the same types of approach. Biogas/Bio-methane technique is used for successful and controlled management and generates methane as fuel and compost caused by leftover food, kitchen waste, and bio-degradable waste (Aravind et al. 2020; Khalid et al. 2021).

The paper reviewed the following constraints:

- Constraint involved in AD from 250 kg municipal solid waste for the production of biogas.
- The design considerations like temperature, waste particle size, hydrogen ion concentration, nature of digester, C/N ratio, organic loading rate, the composition of waste, retention time, moisture content, and cost are described and also discussed as cost-effective, environment-friendly, and optimally designed digester of 250 kg kitchen/municipal solids waste.
- AD processes are straightly connected to all aspects to improve methane yields, such as chemical, operation, and microbiological aspects. These literature studies have demonstrated that the energy potential of AD is to recover at a high priority level.
- There are quite a few other issues that have been addressed in previous research in AD systems, such as C/N ratio, pH, particle size, temperature, alkalinity loading rate, and retention time.

5.2 Literature Survey

Biogas is an eco-friendly heating energy source and also a combustible mixture of gases. It consists of methane (CH_4), carbon dioxide (CO_2), and is also produced from bacterial decomposition of organic compounds with AD. The biogas production from food waste is a complex method in which different type of bacteria are involved (Kadier et al. 2019). Table 5.1 shows the percentage composite of CH4 which usually ranges from 50 to 65% produced while that of CO_2 25–40 and other gases from AD.

Using AD to produce sustainable energy in tropical regions by converting biomass waste into bio-energy products is an opportunity. Energy demand has been increased and also there is a shortage of fossil fuels. Therefore, the awareness of people worldwide has moved toward the biogas energy source (Khalid et al. 2021; Kadier et al. 2019).

Table 5.1 Composition of landfill gas and biogas (Voelklein et al. 2019; Bonk et al. 2019)

S. no	Content	Landfill gas	Biogas percentage (%)
1	Methane, CH_4	35–65	50–65
2	Carbon dioxide, CO_2	15–40	25–40
3	Carbon monoxide, CO	–	1–5
4	Nitrogen, N_2	15	0–3
5	Hydrogen sulfide, H_2S	5 ppm	100 ppm
6	Oxygen, O_2	0–5	0–2
7	Ammonia, NH_3	0–5	0–2
8	Total chlorine as CI	20–200 Mg/Nm^3	0–5 Mg/Nm^3

5.3 Methodology

The breakdown of feedstock without oxygen is encouraged by the amalgamation of bacteria at each phase of the digestion process, prompting the decomposition of feedstock and incorporating CH_4 gas as the principal component with a mixture of gases (Ali et al. 2019; Kasirajan and Maupin-Furlow 2020). The chemical reaction sequences in these steps are also described (Dar et al. 2021).

The entire biogas generation from compound or straightforward organic matters can be divided into four chemical reactions.

5.3.1 Hydrolysis Reaction

In hydrolysis reaction, acid, base, and water can be used to step up the reaction in the presence of enzymes. In this reaction, starch, cellulose, and simple sugars can be broken down by water and enzymes. The enzymes are exoenzymes of cellulose, proteins, etc. from a number of bacteria, fungi, and protozoa in AD see Eq. (5.1) (Zhurka et al. 2020; Piotrowska-Długosz 2020).

$$(C_6H_{10}O_5)n + nH_2O \rightarrow nC_6H_{12}O_6 + nH_2 \tag{5.1}$$

The cellulose conversion in Eq. (5.1) involves the breaking of the β-1,4-glycosidic linkage. In connection with this stage of AD, insoluble cellulose consists of organic compounds that are converted. The dissociation of water from protons (H+) and hydroxide ions (OH−) results in the formation of homogeneous and/or heterogeneous acid catalysis with the presence of species. Bacteria cells can be used to break chemical bonds to form soluble compounds. Some are insoluble in organic H_2O, and microorganisms in AD are responsible for the formation of soluble compounds.

5.3.2 Acidogenesis Reaction

During acidogenesis, the molecules are further broken down into volatile fatty acids, NH_3, H_2S, and H_2 by bacteria. In other words, soluble monomers are transformed into small organic compounds such as alcohol (ethanol, methanol), ketones (glycerol, acetone), and volatile acids (butyric, formic, lactic, propionic, succinic acids) in this process (Auma 2020). Equations (5.2) – (5.4) show the acidogenic stage:

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2COOH + 2H_2O \tag{5.2}$$

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \tag{5.3}$$

$$C_6H_{12}O_6 \rightarrow 2CH_3COOH \tag{5.4}$$

These organisms are able to live under both aerobic and anaerobic conditions with coli, Desulfomonas, Escherichia, Micrococcus, Peptococcus, and Streptococcus in isolated species. However, the major determinants of bacteria that predominate the properties of the material used as feedstock.

5.3.3 Acetogenesis Reaction

In this process, acetogenesis bacteria reacts, and products consist of acetic acid, CO_2, and H_2. Equations (5.5) – (5.8) represent the reactions related to the acetogenesis stage:

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 4H_2 + CO_2 \tag{5.5}$$

$$CH_3CH_2COO^- + 3H_2O \rightarrow CH_3COO^- + H^+ + HCO_3{}^- + 3H_2 \tag{5.6}$$

$$CH_3CH_2OH + 2H_2O \rightarrow CH_3COO^- + H^+ + 2H_2 \tag{5.7}$$

$$HCO_3 + 4H_2 + H^+ \rightarrow CH_3COO^- + 4H_2O \tag{5.8}$$

Several bacteria contribute to acetogenesis, such Syntrophomis wolfci, Syntrophobacter wolinii, butyrate decomposer, propionate decomposer, Peptococcus anaerobes, Actinomyces, Clostridium spp. and lactobacillus are acid formers. In the previous step, volatile fatty acids are produced, which are further broken down to the formation of CH_3COOH, CO_2, and H_2 in the acetogenesis step by binding to hydrogen-producing acetogenic microbes. Some amount of H_2O from the previous steps serves as an electron source to aid in the transformation of the VFA (Anthony et al. 2019).

5.3.4 Methanogenesis Reaction

The last phase is the methanogenesis reaction of AD. These intermediate products formed in the other phases converted into the key product methane CH_4 (Logroño et al. 2020). The reaction Eqs. (5.9) – (5.14) represent the condition that takes place in the methanogenic stage:

$$2CH_3CH_2OH + CO_2 \rightarrow 2CH_3COOH + CH_4 \tag{5.9}$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \tag{5.10}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{5.11}$$

$$CH_3OH \rightarrow CH_4 + H_2O \tag{5.12}$$

$$CH_3COO^- + SO_4^{2-} + H^+ \rightarrow HCO_3 + H_2S \tag{5.13}$$

$$CH_3COO^- + NO^- + H_2O + H^+ \rightarrow 2HCO_3 + NH_4^+ \tag{5.14}$$

The conversion of CH_3CH_2OH into CH_3COOH is represented in Eq. (5.9) and is further converted into CH_4 and CO_2 as represented in Eq. (5.10). The formed CO_2 reacts with H_2 and is converted into CH_4 gas as represented in Eq. (5.11). HCO_3, H_2S, and NH_4^+ are formed in Eqs. (5.13) and (5.14) (Voelklein et al. 2019; Bonk et al. 2019).

Based on these four steps, a biogas digester combined with a crusher has been developed to study the production of biogas. The CH_4 content in biogas streams exceeds 50% and CH_4 emissions to the environment result in a resourceful hydrocarbon waste that also has a greenhouse warming potential 23 times greater than CO_2. Therefore, adequate consumption and collection of the CH_4 limited in biogas ward off emissions of CH_4 to the environment.

5.4 Design Consideration of the Bio-Gasification

The generation of gas is affected by various factors. Some of the environmental factors also influence bio-gasification (Schulzke 2019; Nsair et al. 2020; Igoni et al. 2008). Some of them are as follows.

5.4.1 Temperature

The optimum temperature range for biogas production is around 25–40 °C and can be achieved without additional heat. Additional heat input is required to raise the temperature to 50–60 °C for additional biogas production. At present, it is observed that this temperature range is normal for biogas production (Igoni et al. 2008; Hamzah et al. 2019).

5.4.2 PH and Alkalinity

Due to excess loading and the presence of toxic materials (acidic), the pH value is reduced below 6.5 and a decrease in the production of biogas is caused. The process is delayed in an inactive state. When the pH value is very low, the loading to the digester is stopped and the recommended time to recover the pH for this temperature range is acquired (Nsair et al. 2019). In general, in AD, pH = 7 is optimum, which is close to neutral.

5.4.3 Nature of Digester

Nowadays, the production of gas from household waste is insignificant since current digesters are not proficient for small-scale uses. Therefore, the nature of feed-stock also needs research. Low-cost community-based digesters, low-tech natural digesters, or modern digesters may be used. Many researchers used digesters like batch systems, high solid, anaerobic sequencing batch reactors, or continuous one or two-stage systems. However, based on the nature of solids, excess digesters are available.

5.4.4 Nutrient Concentration

An ideal carbon: nitrogen ratio of 25:1 is to be maintained for efficient plant operation in the digester [48]. If the C/N ratio is too high, in that case, biogas production can be improved to N_2 and vice versa. If nitrogen is too high, it inhibits methanogenic activity. Carbon provides energy to maintain microorganisms, while N_2 helps build their cells. This can be increased by adding carbon. In AD, not only does it convert plant material into CH_4 gas, but it also releases plant nutrients such as potassium (K), nitrogen (N), and phosphorus (p). It is also converted into compost which can be useful for plants. 22 and 25 C/N ratio is best for AD of food waste (Bougrier et al. 2018; Yuan et al. 2019).

5.4.5 Loading of Crushed Slurry

The loading rate of crushed slurry is the biological translation of a reactor. It determines the amount of volatile solids that are possible as inputs to the digester. The feed rate is given by the mass of total solids (m-kg) fed per day, divided by the ratio of total solids (Ts) in the mixed slurry (Babaei and Shayegan 2020). Hydraulic loading is also an important factor for digester volume. A high organic loading rate may cause a rise in fatty acids and result in low biogas yield. This will lead to the mass death of methanogenic bacteria, decrease in pH, and propagation of acidogenesis.

5.4.6 Composition of Food Waste

The composition of solid waste (fruits and vegetables) is an essential consideration to predict efficient design. Residential, commercial, and institutional establishments such as cafeterias or canteens are active sources of food waste. When an excess of protein is followed by carbohydrates and cellulose and results, methanization is accelerated. In line with previous literature, legumes and milk powders show wide variations among compound constituents. In general, legumes show a high content of milk and carbohydrates and confirm a high lipid content (Sarker et al. 2019).

5.4.7 Effect of Toxins

The presence of toxic substances in AD, such as chlorinated hydrocarbons (such as chloroform) and other organic solvents, is mostly toxic to digestion. This is the important factor that prevents the production of gas. The toxins are difficult to remove if the digester is badly poisoned. In this case, before loading the fresh solution, the digester should be emptied and cleaned with plenty of water (Nsair et al. 2020; Annibaldi et al. 2019).

5.4.8 Retention Time

The time during of feedstock remain in the reactor is known as the retention time. 15–30 days for mesophilic digester and 12–24 days for thermophilic are optimal retention times for complete biological conversion. It depends upon the intended use of digested material, type of substrate, and environmental conditions. For reducing the instability of the digester, parameters like temperature, hydraulic retention time, and organic loading rate must be monitored.

5.4.9 Particle Size of Waste

The particle size of waste id directly affects the breakdown in AD. Particle size can be reduced by grinding, crushing, and shredding. Hence, these methods increase the surface area for microbe's action and eventually recover the efficiency of the digester. Mostly, mechanical grinding, thermal, chemical, microwave, ultrasound methods are used for the disintegration of waste (Gollakota and Meher 1988).

5.4.10 Cost

Construction and maintenance costs, capital and operating costs, substrate receiving, and waste processing are essential considerations in the selection of the type and size of the digester (Babaei and Shayegan 2020; Sarker et al. 2019).

5.4.11 Sun Rays

One more factor of sun rays is the most important to maintain the biogas depending on the solar intensity of the atmosphere.

5.4.12 Moisture Content

An anaerobic digestion process with 70–80% moisture is carried out at different levels. The bioreactor operates at 70% moisture content and produces more methane than bioreactors operating at 80% moisture content. Hence, high moisture contents usually facilitate AD. However, keeping the availability of the same water level is very difficult throughout the digestion cycle (Gollakota and Meher 1988).

5.5 Operational Performance Data

The main factor affecting biogas production are pH, chemical oxygen demand, volatile solid, total solid, time, temperature, hydraulic retention time. Table 5.1, 5.2 show a literature review on biogas production from municipal solid waste from 2010 to 2021.

5.6 Kitchen Waste-based Biogas Plant Design

5.6.1 Digester

The digester is to undergo the fermentation of the food waste which is available in the hostel mess and inside the premises of the college. Figure 5.1 shows the biogas digester, which is installed at Rewa Engineering College, Rewa. The digester is designed to have the daily food waste with 250 kg maximum per day. The retention time is 30 days and the waster added is 100ltr max. The digester has 1 inlet, which is accompanied by the crusher (2hp motor) to crush the waste to 5 to 8 mm size. The outlet is attached with the 4″ diameter pipe to carry the manure.

5.6.2 Floater

The floater is used to collect the biogas generated by the fermentation of the food inside the digester. The floater is also called the floating dome of the digester. The biogas generated/produced due to anaerobic fermentation of the food waste is collected in it. The floating dome, as the gas is produced, is lifted automatically, and as the gas is used, the dome comes to its original form (means touches the digester). For the proper function of the floater, always check the liquid in the water jacket (oil/water can be used in the jacket). Check the size of the floater in the manual. The floater is attached with the flexible outlet pipe to suck the biogas and to transfer it to the filter at the pressure of 5 bar, with the help of a small booster pump (Fig. 5.2).

Table 5.2 A literature review on biogas production from municipal waste (Gollakota and Meher 1988; Izhar et al. 2021; Masih et al. 2019; Suelen et al. 2017; Akpan et al. 2015; Sathish and Vivekanandan 2015; Joel et al. 2015; Dasgupta and Mondal 2012; Biswas et al. 2010)

Sources	Waste material	pH	C/N ratio	Temp	Total solid	Volatile solid	Volatile fatty acids	Retention time	Methane yield
Izhar et al. (2021)	Kitchen waste: University canteen Fruit and vegetable waste	5.08 to 5.28	13.98–17.21	42	22.17 7.94	17.87 6.74	–	80 days	0.642 m3 CH_4/kg VS added
Masih et al. (2019)	Cattle dung using with jaggery	5.7 to 7.3	46.4	12 to 24	12.5% to 10.7%	84.6% to 80.9%	1189 to 1110 mg/kg	Nine week	40 l/kg
Suelen et al. (2017)	Fruit and vegetable waste	8– 8.2	34.7	35	–	54.6%	3526.6	20 days	396.6 Nml/gVS
Akpan et al. (2015)	Biodegradable component of MSW in Nsukka metropolis	6.7 to 7.1	–	28–37	–	–	–	28 days	84,277.17m^3
Sathish and Vivekanandan (2015)	Using industrial waste (press mud)	7.1	Less than 18	30–35	–	–	–	45 days	0.68 m3
Abishek et al. (2015)	Using fungi culture with methanogens	6.7	–	30–37	75.55%	93.36%	–	60 days	59.3%
Dasgupta and Mondal (2012)	Bioenergy conversion of Varanasi's	8.9	25–30	–	30%	80%	–	15 days	0.40 Nm3/kgVS
Yilmaz and Demirer (2011)	Cattle manure: Effect of phase separation	6.5 to 7.5	–	35	–	35%	1700 and 1300 mg / l	57 days	313 and 221 ml CH_4/g.VS
Biswas et al. (2010)	Growing up biogas yield of compost by waste	–	–	180	20%	14.8%	–	10 min	136%

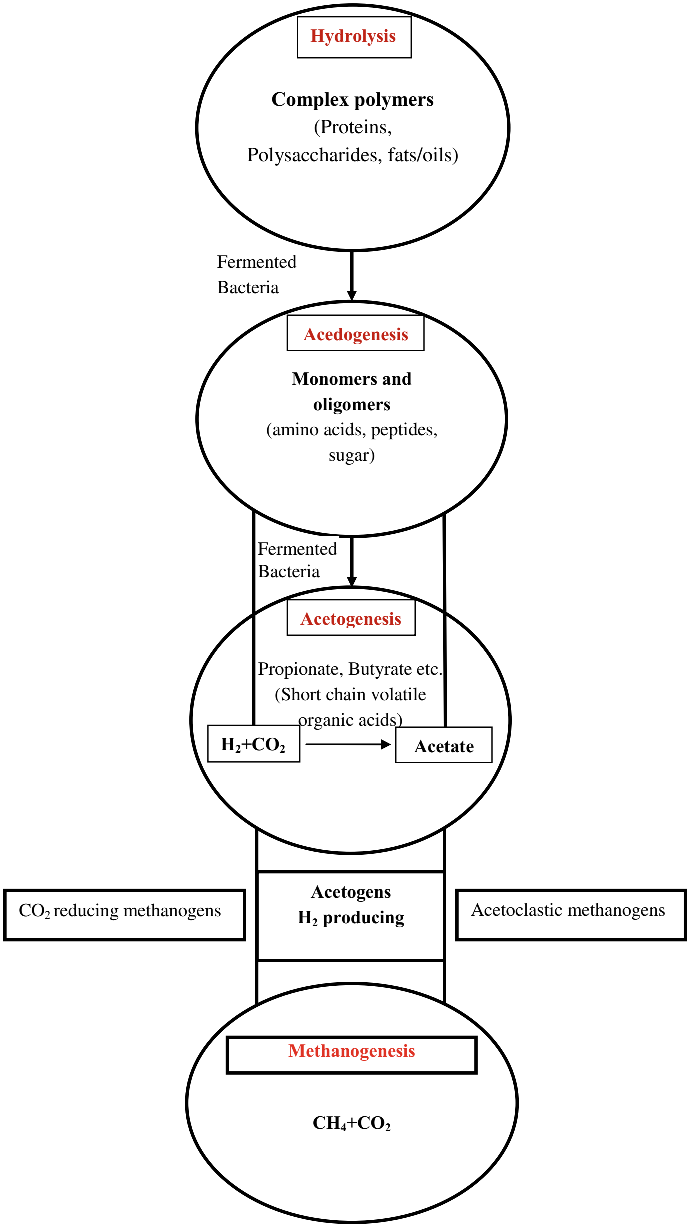


Fig. 5.1 Anaerobic digestion process

Fig. 5.2 250 kg Kitchen waste biogas digester installed at Rewa Engineering College, Rewa, Madhya Pradesh

5.6.3 Filter Unit

The filters use to filter the CO_2, H_2O, H_2S from the raw biogas and make it effective to 90 to 94% methane (separation of other gases and retaining the CH_4). The technique used for filtration is PSA.

Three different cylindrical vessels ate used with adsorption material filled inside them to do the surface adsorption and then released from their surfaces after the period as mentioned. In this process, biogas is compressed into 4–10 bar pressure. Compressed raw biogas is fed to multiple vessels filled with adsorbent materials. In this process activated carbon, zeolites, and other materials (titanosilicates) are engaged as an adsorbent. These adsorbents have a high surface area due to the porosity and filtered CO_2, H_2O, and H_2S from the biogas in contact with these adsorbent materials.

The adsorbents become saturated with CO_2 after a certain time, and the column needs to be regenerated by reducing the pressure. Normally, the regeneration of biogas is pressurized at vacuum. The adsorbed material is toxic by H_2S because it adsorbs H_2S irreversibly. To overcome this issue, the PSA process also includes an initial H_2S removal step. Another adsorption vessel removes the moisture of this biogas. Figure 5.3 shows biogas filtered vessels in which pure methane is recovered at the top of the final column with very little pressure drop.

Fig. 5.3 Biogas upgrading system installed at Rewa Engineering College, Rewa, Madhya Pradesh

To simulate a continuous process, multi-column arrays are used. Storage tanks with a single column can also be used for smaller size applications. They are connected with biogas meter to read raw biogas. The most important property of pressure swing adsorption technology is that it can be adapted to biogas purification systems in any location in the world as it is available at hot or cold sources.

5.6.4 Biogas Analyzer

Three sensors-based problem systems are used to analyze the flowing gases at the pressure of 0.5 l/m. The analyzer is having an input (for biogas) of 4 mm with a soft, flexible pipe. The analyzer runs on the direct supply and also has the 6v battery inside the apparatus. The display shows the data for CH_4, CO_2, and H_2S. The reading can also be stored in the apparatus and also be transferred to the computer with the cable provided. Size of the apparatus is 9” × 4” × 7”, weight around 250gm.

5.7 Procedure

Check all the connections of the pipes and nozzles are airtight (prevent the leakages of the gas. The digester is to be provided with a 5A power supply and connected to the panel of the plant, and then the water jacket is to be filled with oil + water (400–500 L). The crusher is ready for feeding.

The first feed of the plant is to be done 1.5–2 tons with the cow dung so that it will help the fast production of the biogas. Now, the daily feeding of kitchen waste (250 kg food waste + water 100 litter) is to be started. After 15 to 20 days, the floater on the top starts inflating with the gas produced in the digester, but it is not sure that it is enriched in methane or not or in other words, the gas is burnable or not (so we should check it by connecting with the burner if the gas is burning. If the gas is burnable, we start with the filtration of the gas. The raw biogas from the digester is forced to enter the filtration chambers at 5 to 6 bar by switching the booster pump. The gas entered in the filter is passed from the flow meter to get the reading (to calculate the volume of the biogas). Calibrate the gas analyzer and use it to take the reading of the filter gas from filters chambers from the sample valves. Three gas readings can be taken from the analyzer CH_4, CO_2, H_2S gas.

5.8 Conclusion

This review paper is based on a 250 kg kitchen waste biogas digester system, which is installed at Rewa Engineering College, Rewa. Some salient features are immerged with this reviewed study that biogas is a better alternative of energy source, produced from the kitchen waste, cow dung, or other wastes. AD processes convert biomass energy into recycling organic waste and reduce harmful effects on the environment. Biogas digesters work in two ways: one is to reduce waste and the other is to generate valuable energy.

According to this review, more sophisticated research is needed for the following:

- Information collection and, based on experiments, design environmentally friendly viable digesters for municipal waste.
- These considerations affect feed rate, feedstock moisture content, fluid flow patterns (such as unsteady and stratified fluid flows), and co-digestion of different feedstocks. However, those highlighted ideas have been widely reported and the advances made in the optimization of AD technology have been confirmed.

In terms of the various potential applications of AD, future work will be devoted to achieving full optimization of the system. Shown is the two-stage biodegradation of food waste system with good capacity and efficiency. Therefore, additional attention should be paid to the development of such digester systems for municipal waste. However, the single-phase should not be overlooked as it is effective.

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