Anaerobic Digestion: Addressing the Problem of Food Waste by Converting it into Biogas

Chetan Patil and Kailasnath Sutar

Abstract In some parts of rural India, biogas production is a crucial energy source. The statistics show that it is equivalent to 5% of total LPG production. It is a promising renewable source of energy. The resources required for biogas production are easily available in rural and urban areas. Biogas is mostly generated by using degradable wastes such as animal dung, agro-waste, industrial waste, poultry waste, vegetable, and food waste (FW), in addition to a combination of a majority of these wastes. The boost in the production of biogas can be helpful in reducing the load on traditional energy resources. Biogas production can be boosted by using various techniques, such as adding different additives, different pretreatment methods, and using the appropriate co-digestion technique. The present article discusses how biogas production can be boosted by using various techniques.

Keywords Biogas · Food waste · Anaerobic digestion · Co-digestion

1 Introduction

Due to the increasing population, industrialization, and urbanization in India, waste generation is increasing day by day. Control of solid organic waste is a main environmental trouble in India. Biomass, which may be solid or liquid wastes such as organically loaded wastewater, municipal solid waste, sewerage, animal waste, agricultural waste, seaweed, food, and vegetable wastes, can produce biogas via anaerobic digestion (AD) [1]. Organic waste is the mainstream for biogas production. Also, another advantage is to prevent the release of odour and decreases pathogens that do the degradation of organic waste through AD. Moreover, digested residues are nutrient-rich and can be utilized as a fertilizer [2]. According to Food and Agricultural Organization (FAO), approximately 30% of the food produced for human intake around the world is wasted in food supply chain control [3]. In many countries,

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wasted food is currently dumped or burned along with other types of combustible waste. As food waste (FW) is organic and rich in nutrients, it is a promising supply for biogas generation and fertilizers via specific degradation processes. As yet, control of food waste has built increasing interest, with biogas, hydrogen, ethanol, and biodiesel as final merchandise. Food wasted worldwide and in Asia–Pacific countries are cereal, rice, sugar, pulses, oil crops, vegetable oil, veggies, beans, onions, peas, fruits, poultry meat, animal fats, and many others [3, 4]. There are different sources of FW such as the commercial food processing plants, kitchens, cafeterias, big restaurants, and domestic kitchens. However, food wastes are classified as grains, green vegetables, husks, vegetable oils, catering wastes, etc. The catering wastes generally contain egg shells, fats, skins, residues from the intestine, undigested gas, and dairy waste [5–7]. AD comes off as the most prominent method for the treatment of organic waste in comparison to other strategies [8]. It is critical to produce biomass from different degradable sources because alteration in properties is challenging [1]. Various approaches have been considered such as: (i) Performance Parameters, (ii) Pretreatment methods [9], (iii) Co-digestion [10] and (iv) Application of different additives [1] to overcome physical and chemical boundaries of the biomass. Figure 1 reports different approaches to convert FW to biogas [11].

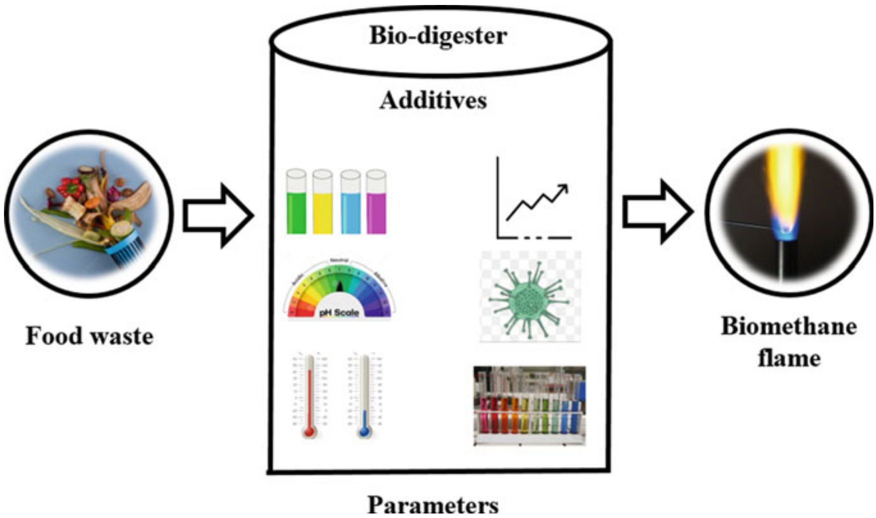

Fig. 1 Different approaches to convert FW to biogas

2 Anaerobic Digestion

AD is a good alternative for recycling degradable waste. The AD process follows a sequence of metabolic reactions, hydrolysis, acidogensis, acetogenesis, and methanogenesis [8, 12]. The first step that is, hydrolysis, depends on the size and shape of the waste particles, surface area, biomass, enzyme production, and surface assimilation. Glucose is the end product of hydrolysis. In the acidogenic stage, propionic acid, butyric acid, acetic acid, formic acid, lactic acid, ethanol, and methanol are the major products that can be transformed from glucose. Among these principal products, acetic acid is seen to be an important organic acid because it makes use as waste to form methane organisms during the process. In acetogenesis, hydrogen plays an important role. In methanogenesis, the step needs to avoid the accumulation of volatile fatty acids (VFAs) and need to avoid a drop in pH that slows down the methanogenesis reaction [13].

In the AD process, practically any organic waste can be biologically converted into another useful end product in the absence of oxygen. The different microbes together biodegrade solid organic waste, that results in biogas and other energy-rich organic compounds as a useful product that is used as fertilizer [8]. In the design and operation of anaerobic digesters attention is given to the quality of feedstock compositions, various pretreatment methods, and reactor design and operation. For example, to get steady biogas, multi-stage anaerobic digesters are superior. They are well known to enhance biogas production as in these digesters, the acidogenic phase and methanogenic phase of the AD process are separated. Moreover, single-stage anaerobic reactors have their advantage, such as low installation as well as running cost, and are well accepted with advantages. To overcome the failure of single -stage anaerobic reactors due to their low acid buffering capacities at high organic loading rates, new strategies have been developed, such as optimizing reactor quality, co-digested feed for long-term and high organic loading rate to improve reactor performance and to get steady biogas [14]. The complicated construction of the digester's increased investment and maintenance costs has bucked up to accept the simple structure and cheaper anaerobic systems. Considering these elements, prefabricated digesters, low-cost biogas digesters, and composite material digesters have been developed for FW and used in many countries to manage the problems of constructed digesters. Constructed digesters have disadvantages such as required long construction periods, comparatively short life spans, high material costs, and maintenance and transportation cost. Prefabricated digesters have advantages such as low price, easily portable, relatively long-lasting, better insulation, corrosion resistance body, etc. It can balance and optimize the operational status of prefabricated biogas digesters. Prefabricated digesters provide an affordable, safer, more long-lasting, and well-organized system to produce energy in many countries [15]. BioPhantom software (Belach Bioteknik, Sweden) is used to monitor and record various parameters consisting of temperature, pH, the quantity of biogas, and the stirrer speed of the digester [16] (Fig. 2).

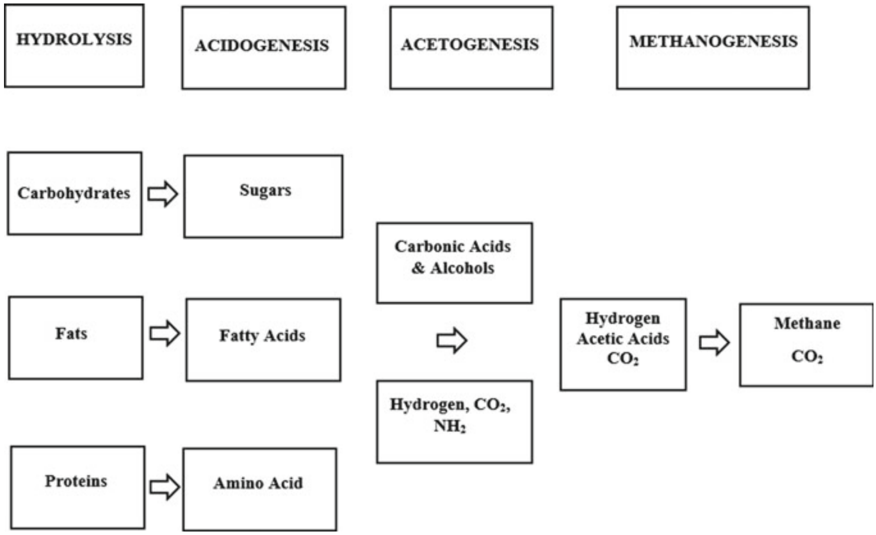

Fig. 2 Successive stages of the anaerobic digestion process [13]

2.1 Necessary Parameters for Anaerobic Digestion

Key parameters such as temperature range, pH range, carbon–nitrogen ratio, particle size, inoculum, mixing, and water content play a vital role in AD processes [17]. Biogas production rate is different at different temperatures. Metabolic activities involved in the AD process get affected by the temperature at successive stages of AD; hence it is an important parameter for biogas production. To maintain the required temperature of the reactor, there is a need for external heating and insulation to avoid inside temperature fluctuations [13]. Maintaining thermophilic (50–70 °C) or mesophilic (35–45 °C) temperature is necessary for the AD process. To maintain higher stability in the process, maintaining mesophilic conditions is necessary, which is easy compared to the thermophilic condition. But the thermophilic condition has the advantage of acclimatization, improves the growth of methanogenic bacteria, reduces retention time, avoids harm to pathogens, improves the digestibility of bacteria, and degradability of solid substrate [10, 18]. The heating approach can also be easily applied to small-size household biodigesters. Insulation and substrate heating are required to maintain a stable digester temperature. Homogeneous heat transfer and uniform heating of the substrate are possible with the in-vessel method [19]. The pH range is different at different AD stages. Hydrolysis is 6.0, methanogenesis is 6.0–7.0, and acetogenesis is 6.5–7.5 [13, 18, 20]. A comprehensive pH range required by fermentative bacteria is 4.0–8.5, and maintaining 6.5–7.2 is favourable for methanogenesis [9]. Factors that affect the pH during the AD process are alkalinity, volatile fatty acid (VFA), Carbon dioxide (CO_2) production, and bicarbonate

(HCO3) [18]. pH is measured using Hach HQ440d p H meter, Thermo Orion, Model 550A pH meter, and WTW Inolab 7110 model pH meter [10, 21].

A carbon Nitrogen ratio in the range of 20–30 was advised to be convenient during the AD process. The C/N ratio of some waste products is Duck dung 8, Water hyacinth 25, cow dung 24, elephant dung 43, sheep dung 19, goat manure 12, pig manure 18, poultry manure 10, straw from maize 60, straw from rice 70, sawdust is above 200 [9, 13, 22]. LECO (TruMac) analyzer was used to determine the C/ N ratio [10].

TS and VFA affect the performance of the acetogens and methanogens. To monitor and control VFAs, different methods such as gas chromatography, liquid chromatography or titrat ion, and back titrat ion was developed, which are cost-effective, speedy, and simple to overcome the defects of traditional methods [9, 16]. TS and VFAs are measured by a TitraLab AT1000 Series Potentiometric Titrator, and analysis was carried out according to SM 2540 D and SM 2540 [10, 21].

The best Inoculum for kitchen waste (KW) will enhance methane yield. Healthy Inoculum collected affects the methane yield [23]. Hence it is necessary to concentrate on the Inoculum to substrate ratio [24]. Additions of active inoculums to biogas digesters that are preferable to low temperatures have an advantage for the AD process [13]. Combining different active inoculums with different proportions can reportedly improve biogas production [25]. To maintain uniformity of fluid in the digester and stability in the reactor, mixing/agitation is necessary. Mixing improves the AD process and biological process [13, 20, 26]. Agitator helps to avoid Scum formation and stratification in the anaerobic digester by combining the biomass with microorganisms [27]. Water Content-Activities of microorganisms get affected by water content in the AD process [13]. Research conducted by Demetriades reported that water content in the range of 60–95% is optimum in the biogas digester [28].

2.2 Pretreatment Methods

There are various pretreatment methods, such as Mechanical, Ultrasound, Thermal, Pressure-de-pressure, Chemical, etc. The particle size of 0.6 mm was considered optimum for maximum methane production. Still, the immoderate reduction of the particle size of less than 0.6 mm of the FW lowers methane production [9, 29]. With experimentation of the Ultrasonic pretreatment method on FW and Cardboard samples, the adequate time of ultrasonic pretreatment is 45 min for a ratio of 100:0 and 80:20, while for 60:40 and 50:50, the ultrasonic pretreatment time is 60 min. It is observed that ultrasound pretreatment enhances the biogas yield [25]. Mechanical pretreatment is completed using a Hollander beater to cut down large size particles of waste food into smaller size particles of waste food to enhance biogas production by increasing the expanse of feedstock. The result shows the pretreatment of waste food for 1800s beating time; the biogas yield is 610.3 ml/g TS at 39 °C,

Table 1 Experimental results of mechanical pretreatment

Experiment number	Beating time (sec)	Temperature (°C)	Biogas yield (ml/g TS)
1	0	35	114.2
2	900	35	365.5
3	1800	35	580.00
4	0	37	115.23
5	900	37	384.42
6	900	37	405.52
7	900	37	415.53
8	900	37	425.01
9	1800	37	590.80
10	0	39	125.21
11	900	39	440.23
12	1800	39	610.33

which is the maximum. It far determined that mechanical pretreatment enhances the biogas yield. The results of the experimentation are shown in Table 1 [30]. In alkali pretreatment, FW is pretreated with NaOH, KOH, and CaO used to degrade the complex organic matter, and it improves the solubilization of FW. It enhances the degradation process during AD, whereas adding 1% CaO to FW showed a better result of methane production as compared to NaOH and KOH [31]. Hydrothermal pretreatment (HTP) on co-digested FW and Sewage Sludge alters the physical structure of FW and sewage sludge, which in turn increases the soluble chemical oxygen demand, solubilization rate, and VFAs. The capillary suction time, time to filter, and decrease in particle size which is beneficial for fermentation. HTP temperature of 140° achieved an increase in biogas production by 50% [32]. Hybrid ultrasonic and alkaline (Na OH) pretreatments were applied on co-digested waste FW and Municipal sewage sludge. Production gets enhanced by 49% by hybrid pretreatment as compared to untreated waste [33]. Agricultural waste such as soybean waste, papaya skin, sugarcane bagasse, rice straw, and blue ginger was used, and they were finely chopped and ground into small particles less than 5 mm in size and mixed with Inoculum by mixing co w manure and distilled water in one: one ratio. As soybean residues contain 40% of total digestible nutrients and other components, it showed the highest biogas production rate [34].

2.3 Co-digestion Technique

In an AD system, varieties of organic wastes are processed with each other in a co-digestion technique. The necessity of the co-digestion technique is to stimulate the breakdown of organic matter, digestion time, and stabilization [35, 36]. Co-digestion enhances biogas production, and factors that affect co-digestion are low ph, accumulation of volatile fatty acids (VFAs), i.e. controlled acidogenesis, and methanogenesis process is necessary to enhance the biogas production [5]. co-digestion of FW and wood chips showed an optimal increase in production yield by 640%. The favorable ratio of FW to wood chips is found to be 0.5. Properties such as moisture content, total solids, volatile solids, and density of FW and wood chips are summarized in Table 2 [37]. Co-digestion of chicken manure and straw in a ratio of three: three and chicken manure and goat manure in a ratio of four: two gives better results [10]. Also, experiments were conducted by processing FW with Low Fruit Vegetable and FW with High Fruit Vegetable waste. FW with High Fruit vegetables showed a stable performance in comparison with Low Fruit Vegetables due to ammonia inhibition and VFAs, which results in low biogas yield and an increase in solid removals [38]. Comparisons on biogas production from KW, from cattle manure (CM), and co-digested KW with CM at room temperature and co-digested KW with CM at 37 °C show the better result, which is summarized in Table 3 [39–41]. At Olive mill wastewater treatment plants, wastewater co-digested with dried FW, chees showed an increasing synergistic effect on methane production. Sewage Sludge with a 5% FCO (Olive mill waste water) mixture resulted in a 170% higher biogas production rate [42].

Hydrothermal pretreatment is effective on lignocellulosic waste biomass by destroying the effect on the lignocellulose structure and decreasing crystallinity in corn cob, which facilitates better co-digestion. When the FW and corn cob were mixed with anaerobic co-digestion at a Volatile Solid ratio of one: three at 150 °C achieved the maximum Cumulative Biogas yield of 4660 mL and the maximum specific methane yield of 316.91 mL/g [43]. As water hyacinth like yams, cassavas, plantains, and tubers which are easily available in Nigeria, contains indigestible recalcitrant complex molecules hence the co-digestion of water hyacinth with FW

Table 2 Properties of food waste and wood chips

Parameter	Food waste	Wood chips
Moisture content (wt %)	87.2	2.7
Total solids (wt %)	12.8	97.3
Volatile solids (wt %)	11.5	64.8
Density (g ml^{-1})	1.1	0.4

Table 3 Composition of biogas of different sample types with different proportions

Sample type	Proportion	CH_4 (%)	H_2S (%)	CO_2%	Other%
KW and water	1:1	68.63	10.97	20.31	0.09
KW, water, and cow dung	4:5:1	71.08	7.59	21.32	0.01
KW, water, and slurry	5:4:1	74.52	7.70	17.66	0.12

decreases the biogas production [44]. Co-digestion of coconut copra and cow urine as co-substrate under the thermophilic condition at 45 °C improved the AD and increased the performance of the digester. Spent coconut obtained from coconut palm is highly degradable, and the addition of cow urine increases the waste's bioconversion faster [45]. Co-digestion of banana peels waste and cow manure where inoculum ratio was maintained at 2. Cow manure improved the AD process as expected due to the presence of active microorganisms required for biogas production [46]. In the domestic wastewater treatment plant, FW is co-digested in the ratio of 2% FW, and 98% domestic sewage sludge rich in organic matter was found appropriate. The current strategy maintained the pH range inside the digester [47]. An Experimentation was conducted on two different 1 m^3 capacity anaerobic digesters for producing biogas from cow dung and kitchen waste in the ratio of one: one with water, and the results obtained turned into an average according per day gas yield of 0.35 m^3 for cow dung and 0.20 m^3 for the kitchen waste at a median substrate temperature of 32 °C and a pH of 6.5– 7.4 for the cow dung and 4.91–7.10 for the kitchen waste [48].

2.4 *Addition of Different Additives/Trace Elements*

The addition of different additives or trace elements favours the AD process. As the trace elements or additives in kitchen wastes are insufficient, their addition favours the process, which can enhance the biogas yield. The AD process is enhanced by the addition of metal-rich substrates or various metal elements as an additive to

Table 4 Overview of the addition of additives or trace elements

Author and year	Additives/ trace elements	Stimulation concentration	General function
Zhang et al. [9]	Sodium (N a)	350 mg/L	Enhances performance at the mesophilic condition
Zhang et al. [9]	Potassium (k)	> 400 mg/L	Enhances performance at both thermophilic and mesophilic conditions
Muratçobanoğlu et al. [21]	Graphite	1–1.5 g/L	It makes possible DIET among distinct microorganisms and enhances biogas production
Xiao et al. [49]	Granular Activated Carbon (GAC)	2.5×10^4 kg	Promotes the degradation of Organic matter, which accelerates the consumption of VFAs
Shamurad et al. [14] Liu et al. [50]	Cobalt(Co)	0.24–10 mg/L	Anaerobic digesters operating at high ammonia concentration activates to stable operation condition

the biomass; only the inhibition from sodium and potassium is avoided. Also, care should be taken to avoid inhibition caused due to high concentrations of light and heavy metal elements [9]. Synergistic effects are observed after graphite addition to FW, cow manure, and co-digested FW and cow manure. The production rate of methane increased by 28%, 67%, and 49.6% respectively [21]. Continuously stirred tank reactors of FW and co-digested wheat straw as co-substrate with or without trace elements enhance methane production. The addition of trace elements such as Co, Mo, Ni, Se, and W to the inoculated digestate fed in batch reactors of FW increased the methane by 45% to 65% [14]. The addition of iron as a trace element affects microbial metabolism; the deficiency of seven enzymes provided by eight microorganisms is fulfilled by adding iron as an additive. For enhancing methane production, these enzymes are necessary during the AD process [41]. In a dry anaerobic digester along with swine manure, granular activated carbon and assimilated sludge were employed, which increased the biogas rate by 10.6% [49]. During the AD process, the addition of different additives such as metal elements, carbon-based accelerants, biological additives, and alkali addition offered remarkable improvement in the AD process. Their dosage and different additives showed a remarkable influence on the improvement of the efficiency of biogas generation [11, 50] (Table 4).

3 Conclusions

The existing review makes evident that AD is one of the useful biological processes for the treatment of a different variety of biodegradable waste. AD is a multi-stage process; involving four degradation steps. For each degradation step, microorganisms are particular and thus could have different environmental requirements which help the AD process. Hence need to concentrate on the necessary parameters. Breaking down the particle size of organic waste increases biogas yield, which is attained using the proper pretreatment method. Inadequate nutrients in the waste inhibit the biogas yield. Co-digestion technique and the addition of trace elements assist in a stable AD process that enhances the biogas yield by reducing the H_2S and CO_2.

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