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Optimization of Biogas Production through Anaerobic Digestion of Fruit and Vegetable Waste: A Review

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Abstract. Anaerobic digestion is the biodegradation of the waste material with the aid of microbes which thrive in the absence of oxygen. Fruits and vegetable wastes (FVW) are a good substrate with potential to produce biomethane and are abundantly available. The optimization of biogas production from FVW was reviewed. A careful consideration when selecting the operating process parameters such as temperature, pH, hydraulic retention time (HRT), organic loading rate (OLR), inoculum to substrate ration (ISR) , particle size and nutrients. The following factors can improve the methane yield from FVW: co-digestion, pre-treatment and digester configuration.

Keywords: Biomethane, Fruit and vegetable waste, Methane, Microorganisms, Optimization

1. Introduction

Anaerobic digestion of organic waste has been applied to produce heat, electricity and fuel for vehicular use. It is the biodegradation of the waste material with the aid of microbes which thrive in the absence of oxygen [1]. The benefit of anaerobic digestion is environmental as it helps in GHG emissions reduction and provides a sustainable form of energy supply. Application of this technology has potential to create green jobs and thus alleviate the levels of poverty in our societies, at the same time helps in waste management [2].

Fruits and vegetable wastes (FVW) are a good substrate with potential to produce biomethane and are abundantly available. FV are prone to decay and sometimes can be obtained from the market in their original state but considered as waste as they would be spoiled. In summer or in warmer climate conditions the process of decay may occur at an increased rate than in colder seasons. They can also be obtained from the beverages industries, restaurants and households.

Though FVW are readily available for anaerobic digestion their degradation process can be complex because of their characteristics. They have high moisture content and often acidic [3], [4]. Hence, a number of factors need to be carefully monitored during the digestion process such as temperature, pH, OLR, ISR, other process parameters. This study seeks to review the optimization of biogas production from FVW.

2. The biogas production process

The conversion of organic matter into biogas is carried out by a consortium of microorganisms through a series of metabolic stages (namely, hydrolysis, acidogenesis, acetogenesis and methanogenesis) and they are shown in Fig. 1.

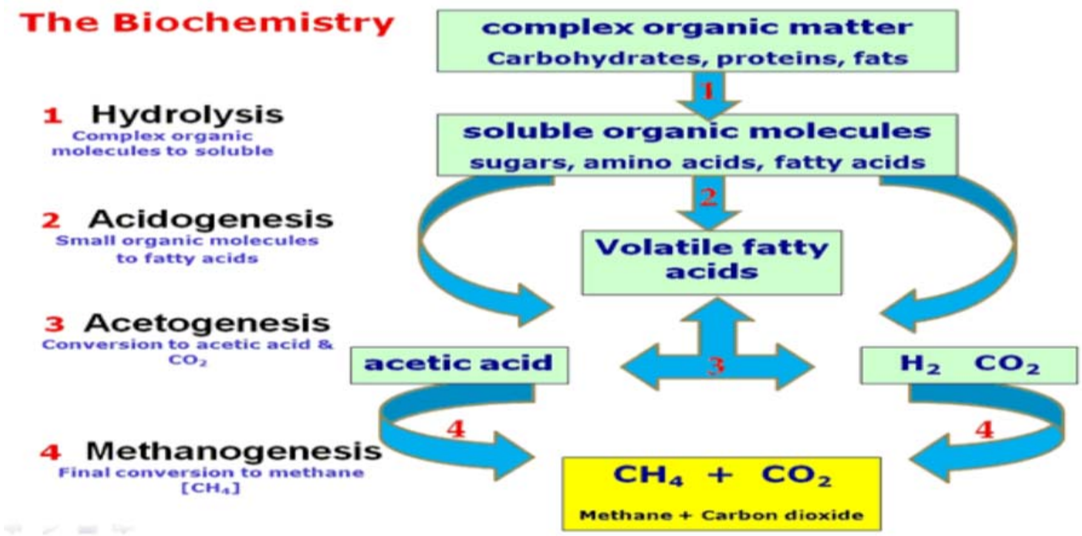

Fig. 1: Anaerobic digestion degradation steps

2.1.1. The main stages in biogas production

2.1.2. Hydrolysis

In the first step complex organic compound such as lipids, protein and polysaccharides are converted into soluble monomers or oligomers (e.g. amino acids, long chain fatty acids, sugars and glycerol) through hydrolysis, also known as liquefaction. This process is facilitated by hydrolytic or fermentative bacteria that release extracellular enzymes. The simple soluble compounds are then fermented by acidogenic bacteria into a mixture of carbon dioxide (CO_2), hydrogen (H_2), alcohol, and low molecular weight volatile fatty acids (VFAs), e.g. propionic and butyric acids; process known as acidogenesis [5].

2.1.3. Acidogenesis

In this acidification step, the sugars, fatty acids and amino acids from hydrolysis are utilised to produce organic acids such as acetic, propionic, butyric and fatty acids, hydrogen and carbon dioxide by the fermentative micro-organism. Amino acids can also serve as energy and carbon sources for strict or facultative fermentative anaerobic bacteria. It is the fastest reaction in the anaerobic digestion of complex organic matter. Increased concentration of hydrogen leads to the accumulation of electron sinks like lactate, ethanol, propionate, butyrate and higher volatile fatty acids. Acetic and butyric acids are the necessary predecessors for methane formation and as a result the concentration and proportion of individual volatile fatty acids produced in the acidogenic stage is important in the overall performance of the system [4].

2.1.4. Acetogenesis

During acetogenesis, alcohols and volatile fatty acids are anaerobically oxidized by hydrogen-producing acetogenic bacteria into acetate, H_2S and CO_2. Acetate can also be formed from H_2 and CO_2 by hydrogen-oxidizing acetogenic bacteria known as homoacetogens. In the final stage, acetotrophic and hydrogenotrophic methanogens transform acetate, H_2 and CO_2 into a mixture of CH_4 and CO_2. Acetotrophic methanogens utilize acetate as a substrate in a process known as acetotrophic methanogenesis [5].

2.1.5. Methanogenesis

Methane and carbon dioxide are formed by mainly hydrogen/carbon dioxide. In the final stage of methanogenesis, methane is produced by two groups of methanogenic bacteria. The first group splits acetate into methane and carbon dioxide and the second group uses hydrogen as an electron donor and carbon dioxide as an acceptor to produce methane. The aceticlastic pathway produces about 70% of methane with the hydrogen pathway more energy yielding than the acetate pathway because it is not rate limiting. It requires that the pressure of hydrogen to be kept low in the system. When the partial pressure of hydrogen increases, it results in accumulation of volatile fatty acids and a decrease in pH leading to failure of the methanogenesis stage and the anaerobic digestion process as a whole. Methane-producing micro-organisms are obligate anaerobes and very sensitive to environmental changes but hydrogen-utilising methanogens have been found to be more resistant to environmental changes [4]. The loading, efficiency and running stability of methanogenesis phase is affected by the terminal fermentation products produced in the acidogenesis phase [4].

Acetotrophic methanogenesis: $CH_3COOH \rightarrow CH_4 + CO_2$ (1)

Hydrogenotrophic methanogenesis: $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$ (2)

3. Factors affecting the anaerobic digestion process

3.1. pH

The microorganisms are sensitive to pH because each group survive at different ranges. They are classified into acidophiles and alkalinophiles, though most favour neutral pH environment [6]. The methanogenic bacteria responsible the production of methane function best at pH range of 6.5 to 7.2 [6]. During the anaerobic digestion pH can drop due to the formation of volatile fatty acids (VFA) and this can affect the methane yield. The acids responsible for pH drop are acetic, propionic and butyric acid. The other factor affecting pH decline is the H_2CO_3 alkalinity concentration [7]. Therefore, a control and balance of pH, VFA and H_2CO_3 alkalinity needs to be maintained. The optimum pH range for FVW was reported to be 6.8-7.6 [8], 6.9-7.57 [9], 7-7.8 [10], and 7.2-7.85 [11].

3.2. Temperature

Temperature is a very important factor of any process as it influences the rate of reaction. Anaerobic digestion is aided by microbial activities which are sensitive to parameters such as temperature. The temperature for microorganism growth is classified into 3, namely, psychrophilic, mesophilic, thermophilic [6]. This affects the digestion process because the livelihood of the microbes is crucial and determines the possibility of the anaerobic digestion. Mesophilic temperature is usually used for anaerobic digestion, though thermophilic temperature can be deemed to improve the rate of reaction and methane yield, the type of substrate also have an effect as well as the type of bacteria present [12].

3.3. Inoculum (ISR)

Inoculum is substance added into a digester to aid the anaerobic digestion process by providing the necessary bacteria for the biodegradation. This process is often called seeding. Slurry from previous digestion can be used, cattle, chicken, pig manure, sewage sludge and slurry from waste water treatment plants can be used. The ratio at which it is added in respect to the substrate is called inoculum substrate ratio (ISR). This ratio is very important as it can either enhance or hinder the complete digestion of the substrate and thus resulting in high and low biogas and methane yields respectively.

3.4. C: N ratio

The mass ratio of C:N:P:S is about 100:10:1:1 in microorganism biomass [13]. It is generally observed that micro-organisms use carbon 25-30 times faster than nitrogen and as a result it is required that a proper composition of the feed is maintained so as to keep the C: N ratio in the desired range [14]. A low C: N ratio may result in ammonium inhibition especially for nitrogen rich substrates. Ammonium poses toxicity to mesophilic methanogenic bacteria. However, C: N ratio above 30 slows down the multiplication of microorganisms which results from the low formation of protein. The optimum C: N ratio is thus 20-30:1 [13], [15]-[17].

3.5. Organic loading rate

The organic loading rate is the amount of solids added into the digester per unit volume per day and is normally denoted as OLR kg VS/L. d. the loading rate helps in determining the amount (mass) of feedstock to be added in a digester per day depending on the volume or size of digester to yield maximum biogas. The knowledge of the OLR for a particular plant helps since feeding over the OLR doesn’t necessarily result in an increase in the gas produced [18]. In a study to improve the biogas production for FVW by [9] , the OLR was reported to be 2.46-2.51 g/L. d for different digesters.

3.6. Hydraulic Retention Time

Hydraulic retention time is the time the solids or slurry spend in the digester during the anaerobic digestion process. HRT differs depending on type of substrate and climate condition with which the anaerobic digestion is performed. For example in tropical climate countries have shorter HRT between 30-50 days, whereas in colder climates HRT can go as high as 100 days [12], [19]. Longer retention times are promoted because they aid in sufficient biodegradation of the organic matter and reduce the possibility of active bacterial population washout, though this may need a large volume digester [12], [18]. Das and Mondal, [20] used the shortest HRT of 15 days and Rao and Singh, [21] the longest HRT of 100 days while digesting vegetable waste.

3.7. Nutrients

The microorganisms require micronutrients for their growth and stability [1]. Some of the nutrients are readily available in most of the substrates, but an addition may be needed when necessary. Nitrogen, phosphorus, and trace elements such as calcium, sulphur, magnesium, potassium, nickel, iron, zinc, cobalt, copper and manganese are good source of nutrients [12], [22], [23]. Addition of these nutrients will lead to improved digester performance and result in improved methane production. Table I shows the optimum concentration of the micronutrients required by the microorganisms.

Table I : The required optimum concentration of micronutrients

Necessary Optimum Concentration	Micronutrients g/m^3
Barium (Ba)	0.05
Iron (Fe)	0.2
Calcium (Ca)	0.03
Cobalt (Co)	0.005
Magnesium (Mg)	0.02
Molybdenum (Mo)	0.005
Nickel (Ni)	0.01

3.8. Surface area/ particle size

Particle sizes of the substrate also have a significant influence on the gas production rate. It is therefore necessary that the particle size of the substrate be not too large as it may result in the digester clogging and difficulty experienced by the microbes in breaking down the substrate [19].

4. Factors that can improve the anaerobic digestion process

4.1. Co-digestion

Co-digestion is the anaerobic digestion of two or more type of organic waste simultaneously. It is often applied with the sole intention of improving the biogas yield and quality, substantiating substrates that generally have low yields and on other process parameters that favours the methanogenic bacteria. The characteristics of the substrate sometimes help in determining the need for co-digestion and also help in finding the pair that has potential to yield more gas and improve the performance of the substrates. Substrates like cow manure, poultry waste, pig waste and food waste are normally used for co-digestion and have been reported to increase the methane yield [24], [25]. Callaghan et al. [25] observed an improvement in the methane yield from 230 to 450 L CH_4/kg VS after increasing the proportion of the FVW to 50% from 20% in co-digestion with cattle slurries and chicken manure. Table II show the advantages and disadvantages of co-digestion.

Table II : Advantages and disadvantages of co-digestion

Advantages	Disadvantages
Better nutrient balance and digestion	Additional digester effluent COD
Increased biogas yield	Require increased pre-treatment methods
Possible gate fees for waste treatment	Require additional mixing

Good by-product (fertilizer for soil conditioning)	Require wastewater treatment
Renewable biomass disposable for digestion in agriculture	Require hygienization
	Restrictions of land use for digestate
	Economically critical dependent on crop

4.2. Pre-treatment

Feed pre-treatment is applied mainly to improve the substrate yield as the complex components are broken down first in this step making it easy for the biodegradation process to take place. The other advantage for pre-treatment is that it helps to speed up the hydrolysis of the substrate and therefore increasing the soluble chemical oxygen demand [26]. There are different techniques applied to aid this which include but not limited to: alkali or acid, thermochemical, ultrasonic pre-treatment; fresh substrate pre-digestion; and ensilage of feed [12], [19].

4.2.1. Types of pre-treatment

A. Alkaline pre-treatment

NaOH is normally used for this treatment. Different concentrations depending on the substrate being studied can be applied. Zheng et al, [27] analyzed the chemical compositions and structures of the pre-treated substrate and reported a reduction in the total cellulose, hemicellulose and lignin contents by 9.3-19.1%. In addition, hot-water extractives increase by 27.1-77.1% lead to an improvement in biogas production. Pre-treatment with 1% NaOH improves in microbial digestibility with 31-42% and has potential to double the biogas yield [28], [29]. Wang et al, [30] reported a 200% increase in biogas and methane yield for fruits and vegetables waste and 63-66% methane volume for digestion at room temperature.

B. Acid pre-treatment

Acid pre-treatment uses HCL with pH of 6-1. A pH of 2 was reported to be the optimal for a batch digester, as it was effective and produced more biogas in a shorter HRT as compared to untreated waste [31]. This pre-treatment is also dependent on the type of substrate being treated and the temperature of the digester. For a semi-continuous digester a 14.3% methane yield increased was reported by Devlin et al, [31].

C. Thermo-alkaline pre-treatment

Thermo-alkaline treatment involves treating the substrate with NaOH at higher temperatures. This normally uses short time unlike alkaline pre-treatment alone. The highest lignin and hemicellulose reduction can be obtained at 100 °C at 1-10% NaOH concentration, over 50% reduction [32]. These conditions also yield to increased methane production. Zhong et al, [33] performed pre-treatment at 70 °C for 2 hours with 0.10 NaOH/TS and observed an improvement in the specific methane yield and digester productivity.

D. Ultrasound pre-treatment

Ultrasonic treatment has been applied to pre-treat sewage sludge, dairy cattle slurry, and industrial meat processing [34]-[36]. It produces high energy yield in respect to the volume of the digester, has room for lower hydraulic retention time, operates at both mesophilic and thermophilic temperature conditions, and high methane yields can be attained [26]. Quiroga et al, [26] reported a 31% increase for mesophilic conditions and 67% increase for thermophilic pre-treatment of co-digested waste through ultrasound.

E. Thermal pre-treatment

Thermal pre-treatment is the application of heat to the substrates which is aimed at solubilizing it and increase the digestibility potential. The sole purpose is to increase the methane yield from the anaerobic digestion process. The pre-treatment focuses on temperature with respect to time. Ferreira et al, [37] reported a 20% increase in methane yield from pre-treatment at 220 °C for 1 minute. Whereas, Menardo et al, [38] obtained 60% increase in methane yield for thermal pre-treatment on wheat and barley straw.

F. Hydrothermal pre-treatment

Hydrothermal pre-treatment has been applied to produce ethanol from lignocellulosic material which helps increase enzyme accessibility in biochemical conversion [39]-[42]. Acids such as sulphuric acid are added to improve the ethanol yield and promote the reduction of cellulose to monomers glucose [43], [44]. Qiao et al, [45] observed an increase in biogas production from FVW by 18.5 % after hydrothermal pre-treatment at 170 °C for 1 hour, with 16.1 % increase in methane yield. In a study by [42] an increase in biogas and methane yield were reported after hydrothermal treatment followed by 5% NaOH addition to the substrate.

G. Milling pre-treatment

The substrates often are in big sizes, especially FVW as sometimes spoilt fruits and vegetables are collected still in their complete state. Hence the biodegradation by the microbes will be hindered as the substrate will not be fully accessible and thus leading to low production of biogas and methane. Hajji et al, [46] recorded a 20% increase in biogas production for particle size of 10 mm treating OFMSW as compared to 20 and 30 mm.

4.3. Digester configuration

The configuration of the digester affects the performance of the anaerobic digestion. The effect can be traced by the methane production from the digesters, this is not limited to the stages but also includes the type of digester used. For example, volumetric, and tabular digester.

4.3.1. Batch digestion

Batch anaerobic digestion is one stage digestion process where all the microbial activity stages take place in one digester. Batch digestion can yield good methane if the operating conditions are monitored and optimized in order to favour the biodegradation process based on the substrate being studied.

4.3.2. Continuous digestion

Semi-continuous digestion is often used to describe a two stage digestion in which the hydrolysis and acid formation step is separated from the methanogenesis step. In respective of the benefits it holds it is not advantageous or feasible for small scale household digesters [12]. Two stage digestion has been reported by [47] to have high methane production.

4.3.3. Agitation and mixing

Agitation (stirring) is normally preferred in anaerobic digesters to improve the biogas yield as it permits for sufficient combination of the substrate and the microorganisms. It helps to maintain homogeneity within the solution, avoids settling of the substrate during the digestion, gives room for process stability in the digester, prevents formation of scum and enhances bacteria affinity. The agitation required for a particular digester is dependent on the type of material being digested [19].

5. Conclusion

The optimization of biogas production from fruit and vegetable waste was reviewed. Both mesophilic and thermophilic temperatures can be applied for the anaerobic digestion of FVW, however mesophilic conditions are often favoured. The optimum pH for AD of FVW ranges from 6.5-7.5. For commercial applications, two stage digestion is ideal and co-digestion with either chicken, cattle or pig manure is advisable for enhanced biogas and methane productivity.

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