ISSN: 1999-1630

SEU Journal of Science and Engineering, Vol. 13, No. 1, June 2019

Performance Evaluation of Three Stage Integrated Anaerobic Process for Waste Treatment to Produce Biogas

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Abstract

Over the last century, fossil fuel has been used to such an extent that it not only induced a serious threat to the environment, but also engendered the necessity to find an alternative of clean fuel. Anaerobic digestion added a new dimension to produce alternative fuel (methane) to solve this issue. Hydrogen can also play a vital role along with methane to mitigate the carbon effect. Many new methods have been introduced to produce H_2 and CH_4. Some of these processes do not show good efficiency when they run individually, but integration of two or three processes can be a good technique to generate green gases efficiently. In this paper three individual processes, Dark Fermentation, Anaerobic Digestion (AD) and Microbial Fuel Cell (MFC) methods, have been integrated together to recover H_2 and CH_4 gas and electricity respectively.

Keywords: Anaerobic Digestion, Waste treatment, Dark fermentation, MFC.

I. Introduction

Organic waste can be found anywhere where human lives. If we do not deal with this waste properly, this may cause serious impact on the environment and human. So an anaerobic digestion (AD) plant, not only reduces waste from the environment, but also energy and agricultural beneficial soil can be recovered from it, thus reducing the greenhouse effect. Increasing of greenhouse effect has drawn the attention for alternative and eco-friendly fuel production. Waste materials possess serious threat to the environment and treatment is also a challenging task. It is found from the study that anaerobic digestion has the best life cycle analysis (LCA) results among all renewable energies (hydro, solar, wind). Few other processes can be added to increase the efficiency of anaerobic digestion plant. Three stage waste management system has been discussed in this article to enhance the output compared to traditional anaerobic digestion process.

II. Litereture Review

Recently Hydrogen has emerged as one of the promising alternative because it can be produced from a renewable energy sources and used in fuel cells with higher efficiency and the by-product is water and heat. There are various methods available to produce hydrogen. The chemical methods of producing hydrogen are associated with non-renewable feed stocks, high temperature process and emission of greenhouse gases. Among the different biological methods of H_2 production, dark fermentation is an anaerobic digestion of organic substances and considered the simplest method of producing bio hydrogen (Liu et al., 2008), (Cardoso and Romão, 2014). Dark Fermentation is derived by group of bacteria using multi enzyme systems for fermentative conversion of organic substrate to bio hydrogen. Dark fermentation reactions occur in the dark at room pressure, thus hydrogen can be produced constantly throughout the day and night. Production of hydrogen gases by fermentation process either involves facultative or strict anaerobic bacteria. Dark fermentation is currently being used by the distilleries and dairies to treat wastewater followed by concentration and incineration biological treatment (Kadier et al., 2016).

Dark fermentation seems one of the most environmental friendly methods of producing hydrogen. The most significant advantage of this process is that it doesn't emit any greenhouse gas during the process. The feedstock for this process can be residual, abundant, cheap, renewable and

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biodegradable product which is not only viable in economic aspect but also advantageous in term of environmental aspects. It is also found that the combined process is reasonably inexpensive for industrial H_2 production (Han et al., 2016).

Microbial fuel cell (MFC), or biological fuel cell, is a bio-electrochemical system that produces electric current with the aid of bacteria by converting chemical energy to electrical energy. These bacteria have electrochemically active redox proteins such as cytochromes. Electrons can be transferred directly from their outer layer to the anode. Furthermore, using CO_2 and light as power source these microalgae are grown in the cathode chamber. There are various MFC systems which are under construction such as Single chamber MFC, Flat plate, UASB type, stack type etc. these bacteria are self-regenerated sustainable and environmentally friendly biocatalyst. They can generate direct electricity from wide range of fuel (e. g. acetate, ethanol, wastewater, etc.). Microbial fuel cell (MFC) is under more future research. It can be a good stepping option for waste water treatment. The required pH level should be 7.0 using phosphate buffer media. The process takes place at room temperature. Microalgae require an environment that is rich in nutrients and salts, carbon which will allow faster growth. Many other factors, such as light, temperature, pH also affect algal growth. Bacteria that can transfer electrons directly to the electrode are Geobactersulfurreducens, Alteromonas, Shewanellasppetc (Baicha et al., 2016).

This system also has the feasibility for scale up as well as the benefit of being economically cost effective. This bio-treatment process is reasonably inexpensive and environment friendly method as the microalgae consume the nutrients from the wastewater for their growth (Baicha et al., 2016). It is found from a research that the MFC technology has good payback period and a positive Net present value for a waste water treatment. Therefore, from the economic and environmental aspect, it can be said that in the near future MFC can be used for large-scale usage for wastewater treatment (Dannys et al., 2016).

III. Integrated process

Bio-hydrogen and bio-methane can play a vital role not only as a security for future energy supply, but also for clean and environmental friendly energy. Among all renewable energy sectors, most probably biogas has attracted the most attention. According to the research, around 4 million tons oil equivalent (Mtoe) of biogas primary energy were produced in EU during 2013, which is 10% more than 2012 (Schievano et al., 2016). So, it can be assumed that lot of research and experiment has done to produce more energy from biomass in the recent years. Traditionally in the past, Anaerobic digestion (AD) probably was the popular methods of producing bio energy. But now lot of new promising technologies have been introduced like dark fermentation, PSA, Bio electrochemical system (MEC, MFC) etc. Among these, Bio electrochemical system is a promising technology for energy-efficient wastewater treatment and sustainable energy generation. In this report, two technologies have been integrated with the traditional anaerobic digestion (AD). Dark fermentation process has been introduced before anaerobic digestion and microbial fuel cell as the post treatment. A simple block diagram of the three stage bio hydrogen and bio methane production is shown below.

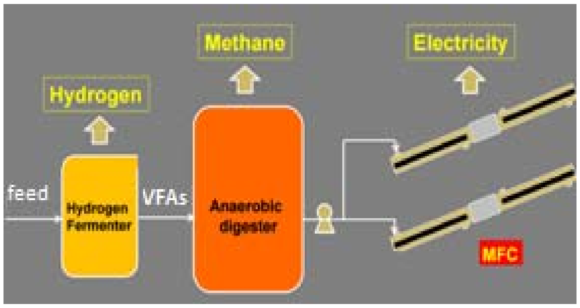

Figure 1: Basic schematic diagram of three stages of integration

III.A Dark fermentation

Hydrogen fermentation can be considered as dark fermentation as it takes place in a vessel under no light and oxygen. The end products of this process are hydrogen and organic fatty acids. Among all the methods of hydrogen production, dark fermentation is probably the most environmentally friendly method as it fermentates the waste materials thus helps to degrade the waste in the process. Technically the first two steps of anaerobic digestion, hydrolysis and acidogenesis are together known as dark fermentation process (Ting et al., 2007).

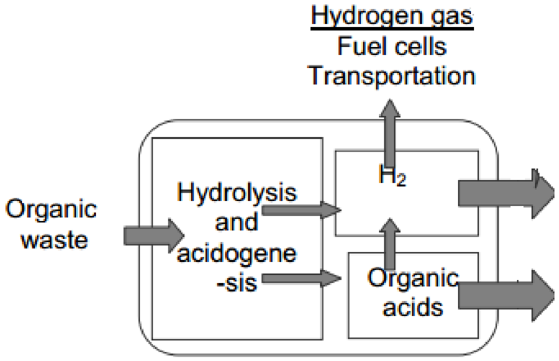

Figure 2: Dark fermentation process.

Waste materials / waste water are used as feedstock to the system. The Waste water is kept in an aerated tank of micro-organisms which is referred as activated sludge or mixed liquor. Organic complex compounds are made of carbohydrates, fats, proteins etc. during fermentation process, in the first stage these complex carbohydrates, fats and proteins breaks into simple compounds of sugar, fatty acids and amino acids respectively. The hydrolic retention time (HRT) for hydrogen production is just 1-2 days where methane production requires HTR of 12-20 days (Wanget al., 2009). At first, the organic polymers like cellulose proteins are decomposed by extracellular enzymes to water-soluble monomers (e.g., monosaccharides, amino acids, glycerine, and fatty acids) and thus made accessible to further degradation. Then these monomers are converted into acetic acid (CH_3COOH), hydrogen (H_2), carbon dioxide (CO_2), organic acids, and amino acids etc., and different groups of bacteria. From here hydrogen gas can be collected as hydrogen fuel. The carbon di-oxide and these fatty acids later can be used for the 3rd phase of the system in microbial fuel cell (MFC). Dark fermentation process produces hydrogen and CO_2, but few other mixture gases like carbon mono oxide, methane, hydrogen sulphide can also be produced. In the below equation, it can be seen that the oxidation of glucose produces 12 mole of hydrogen.

$$C_6H_{12}O_6 + 6\,H_2O \rightarrow 12H_2 + 6CO_2$$

Different type of feedstock and different pathway of fermentation will yield different amount of hydrogen. Hydrogen production is also determined by the butyrate/acetate acid ratio. If the targeted end product is acetic acid, then maximum 4 moles of hydrogen can be produced from 1 mole of glucose as shown below.

$$C_6H_{12}O_6 + 2H_2O \rightarrow 4H_2 + 2CH_3COOH \text{ (acetate)} + 2CO_2$$

If the end product is butyrate acid, then theoretically 2 moles of hydrogen can be produced as shown below,

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2H_2 + CH_3CH_2CH_2COOH \text{ (butyrate)} + 2CO_2$$

Clostridia, methylotrophs, rumen bacteria, methanogenic bacteria, archaeaetc are the responsible bacteria for hydrogen production in fermentation process. The process can be impacted by environmental factors like pH, temperature etc. But most common temperature is 35-55°C for conducting dark fermentation experiments. It has been found from various researches that the optimal pH for dark fermentation is around 5.0-5.5 (Liu et al., 2008). After the production of bio-hydrogen, the rest of the organic matters are sent for further process to the anaerobic digester (Logan et al., 2008), (Liu et al., 2008).

III.B Anaerobic digestion (AD)

Once the dark fermentation process is over, then the effluent of dark fermentation phase is the feedstock for the 2nd phase of integrated system (anaerobic digestion). The two key bacterial groups become active during the last two stages (acetogens and methanogens) stages of methane production. Dividing the traditional one stage anaerobic digestion provides better stability of the microorganism, process control and enhances the production by around 10-13% (Nasr et al., 2012). In acetogenesis stage, the acids and alcohols break into acetic acid, hydrogen and carbon dioxide through acetogenic bacteria which are the major compounds for biogas production.

The effluent from first phase like volatile fatty acids and intermediates (alcohols, lactic acids etc) converts into acetate and carbon-di-oxide. These are the reaction that takes place in the reactor during acetogenesis phase,

$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO^{3-} + 3H_2$

$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$

$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 2H_2 + H^+$

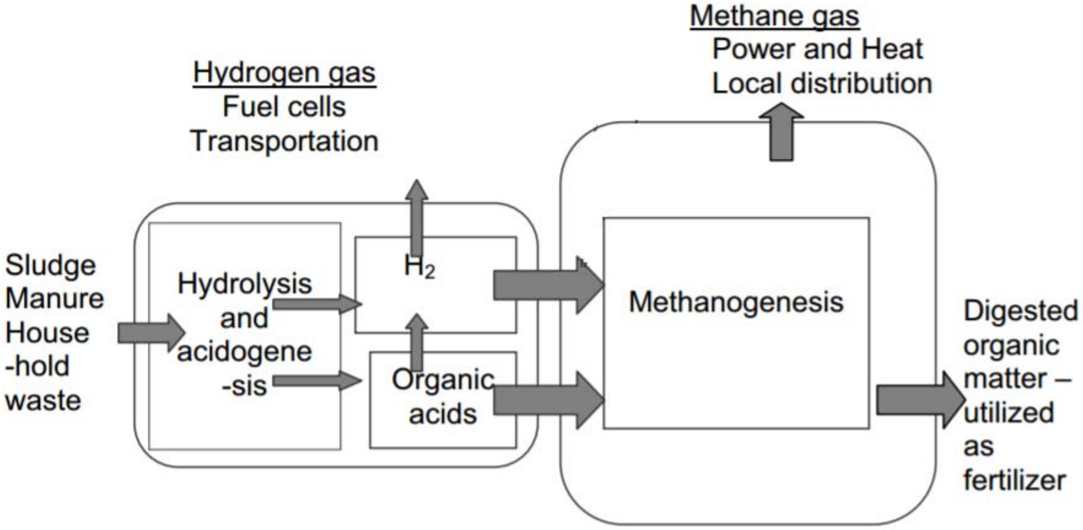

Figure 3: Integration of anaerobic digestion process with dark fermentation

The process is sensitive to any changes in physical and chemical conditions (temperature, pH, hydrogen partial pressure etc.). Temperature is one of the most important factors for any AD plant. The optimal temperature for mesophilic process is 25-40°C for microorganisms to grow while the thermophilic system runs most efficiently at higher temperature ranges of 45-80°C. The pH range should stay between 4-5.5 for the better performance of microorganisms. Nutrients are another important factor which enhances the growth of bacteria. Higher amount of nitrogen will reduce the biogas production and lower amount of nitrogen can cause ammonia build-up and higher pH values. Methanogenesis is the last biological stage of anaerobic digestion. During this process methanogens use the intermediate products to convert them into methane, carbon dioxide, and water. The pH range should stay around the neutral mark (6-7).

There are three types of output of this AD process. One is solid part which is digestate and another part liquid effluent and the most important output is the gaseous (biogas) portion. This biogas is a mixture of methane, hydrogen, CO_2, CO, H_2S etc. Later this biogas requires rectification and up gradation before it can be injected into the national gas grid or for further transportation fuel. The solid digestate can be used as soil fertilizer for the farmers. This solid part has good nutrients in it. The liquid effluent again can be sent for more treatment (if needed) before it can be released to open environment.

III.CMicrobial Fuel Cell (MFC)

Microbial fuel cell is one of the new methods of recovering energy from the direct conversion of organic matter into electricity by the use of bacteria. Bacteria in the microbial fuel cell can dispose organic matter and release electrons to an external circuit to generate electricity. This basic structure of the fuel cell is consist of an anode, cathode chamber with a proton membrane to separate them (as shown in the below).

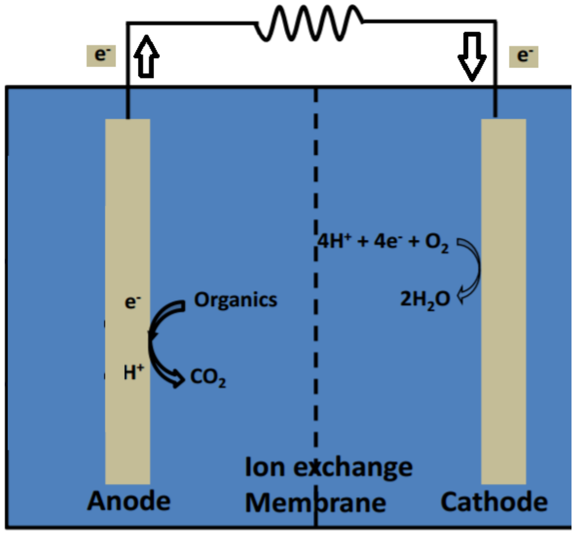

Figure 4: Basic structure of MFC

The anode chamber requires to be kept in anaerobic condition as the presence of oxygen will inhibit the production of electricity. The feedstock of this process is the liquid organic acid i.e. acetic acid/butyric acid from the dark fermentation process. The bacteria will oxidize the organic substance to produce electrons and protons. The other by product at anode chamber is carbon di oxide. The electrons will travel through the external circuit while the protons will pass through the membrane. In the cathode chamber, these electrons and protons will combine with oxygen to produce water.

Anode: $C_2H_4O_2+2H_2O \rightarrow 2CO_2+8e^-+8H^+$

Cathode: $2O_2+8H^++8e^- \rightarrow 4H_2O$

Above are the reactions that take place at anode and cathode. The ultimate productive output of MFC is electrical current. There are various types of MFCs which are available such as Single chamber MFC, Flat plate, UASB (Upflow Anaerobic Sludge Blanket Reactor) type, stack type etc. The performance of MFCs is depended on few factors like oxygen flow of in cathode, organic matter at anode, permeability of membrane, electron shuttle from anode compartment to anode etc (Rahimnejad et al., 2015). The three stages of the whole system are illustrated below.

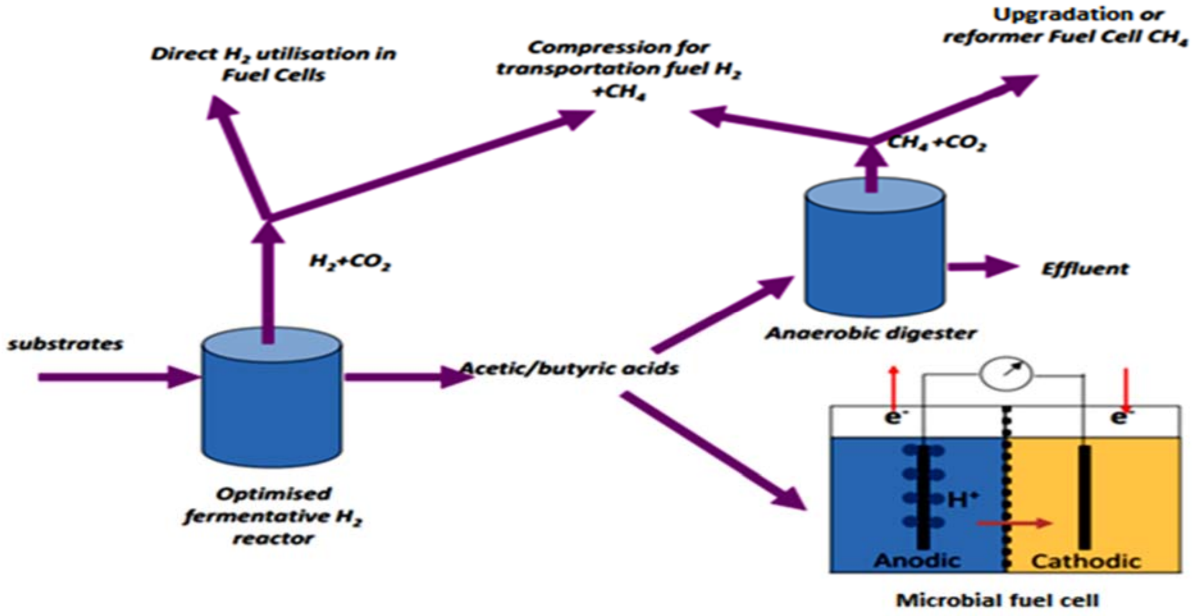

Figure 5: Overview of three stage integrated process

The three main resultant outputs are bio hydrogen from dark fermentation stage, bio methane from AD and electricity from microbial fuel cell. Among these three outputs hydrogen and electricity can be used directly. But biogas needs some modification before final use.

IV. Challenges & Improvements

There are few challenges that may occur when integrating these systems together. The residence time for AD is 1-2 weeks where as for dark fermentation it is just 1-2 days. Temperature is another issue with these systems. Like AD runs over 30 ºC, but other system runs in room temperature. pH values needs to be checked in every stage (Schievano et al., 2018). The untreated effluent needs polishing process. The output of AD is biogas which is a mixture of many compounds. So this gas needs to upgrade to convent in methane before it can be used as fuel. Since the feedstock for AD is solid organic, so the plant will produce solid digestate. If the protein amount is high, the plant has to deal with ammonia gas. The power density of MFC is low. The selection of microbial catalyst is another concern. The production MFC can reduce the internal resistance and poor oxygen reduction kinetics at cathode (Dartmouth, 2018).

V. Conclusions

It can be seen that if three stages are being used rather than one stage anaerobic digestion, the energy recovery is far better. H_2 gas, methane gas and electricity can be recovered separately from each of the different stages which make the process more efficient. Upgrading process can be added later to convert the biogas into pure methane for grid injection. Though some limitation and challenges are there for each systems, but more researches are going on to meet the challenges and make these processes more efficient.

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