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Anaerobic co-digestion of animal manures and lignocellulosic residues as a potent approach for sustainable biogas production

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ABSTRACT

Anaerobic digestion is a versatile biotechnology for conversion of organic wastes to valuable biogas. Anaerobic digestion of manure is making the most of it, as the process allows simultaneous bio-energy generation, production of nutrient rich soil amendment, reduced emission of greenhouse gases and odor control; it is thus in line with climate friendly farming practices. Despite the enumerated advantages, the potential of manure for biogas production is not fully utilized due to the low and imbalance carbon to nitrogen (C/N) ratio in animal manures. To satisfy the anaerobic digestion requirements and to compensate the carbon deficiency of manure, there should be another carbon-rich substrate to be co-digested with manure to improve its characteristics for anaerobic digestion; lignocellulosic biomass residues seem promising for this purpose. This work presents a review on anaerobic co-digestion of animal manure and lignocellulosic feedstock for biogas production. Several research studies conducted on co-digestion of these organic wastes are described and reviewed. The impact of numerous parameters including temperature, pH, organic loading rate (OLR), hydraulic retention time (HRT), C/N ratio, alkalinity and concentration of volatile fatty acids (VFAs) on the performance and stability of the co-digestion process is extensively discussed. The influence of various pretreatment methods including physical, chemical and biological pretreatments on providing well-prepared substrate for anaerobic co-digestion and thus enhancement of biogas production is discussed. An overview of the most significant factors and intermediates which can inhibit or even cease the process is also presented.

1. Introduction

The environmental implications of animal manure disposal have motivated authorities to seek for strategies which could lead to “sustainable animal farming”. Towards this transition, solutions that could help to transform manure into value-added marketable products sound green and caring. As a biodegradable product, manure should not be disposed of in landfills as it contains significant levels of nutrients and pathogens. Any improper management of this valuable waste can contaminate soil, air and water and also cause harmful microbial build-up in the environment. Among the best manure management practices which also contribute to sustainability is anaerobic digestion through which, simultaneous waste treatment and bio-energy production could be achieved.

Traditionally, manure has been used as a valuable fertilizer for virtually all farming operations to provide required nutrient for crop growth. An ordinary cow manure is likely to contain roughly10 lb nitrogen, 5 lb phosphate and 10 lb potash per ton [1]. Manure also contains beneficial microorganisms which can enhance soil structure and biological activity. Nevertheless, over the past 50 years, use of manure on many farms has gradually declined due to several reasons including: i) specialized farms use with increasing separation of breeding and cultivation (livestock and crop production), ii) cost considerations of manure transportation and (iii) increased availability of synthetic fertilizer with desirable compositions and concentrations at cheaper prices. Today, mass-production of animals in factory farms to provide food requirements generates staggering amount of manure; almost 130 times that of human waste produced in the United States [2]. Understanding how to manage the huge amount of manure daily produced is challenging and of course a wiser utilization of the manure on the farm is in demand. The same nutrients that make manure a valuable commodity also make it a threat to the environment. Inappropriate handling of manure may lead to destructive run-off, containing bacteria and nutrients which contaminate local ground water and threaten public health. Significant nutrient loss during collection, storage, distribution and utilization of manure is almost

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inevitable. Manure storage in open air, particularly in humid tropics with high rain fall, can conclude to 70% nitrogen loss within 24 h which happens through ammonia (NH_3) volatilization and nitrate (NO_3^-) leaching [3]. Leaching of P (P_2O_5) and K (K_2O) also occurs when rain fall is high. In some countries, manure is first treated in lagoons and then directly discharged into the surface water; this implies almost complete loss of organic matter and nutrients from the manure. When manure is directly discharged into the surface water, decomposition of easily degradable fractions starts immediately which consume all dissolved oxygen and creates an anaerobiosis condition in water. The heavy load of nutrients in the manure will deteriorate the condition by contributing to water eutrophication and heavy metal toxicity [4]; this will eventually conclude to the death of water fauna and flora and reduce the aquatic life of a river to zero. Moreover, the methane and carbon dioxide produced by anaerobic self-remediation of manure can largely contribute to the global warming. In manure management plants, the challenge is thus to find ways to maximize the benefits of manure while protecting water resources and environment. Anaerobic digestion of manure has attracted considerable attention in this regard; it has the potential of tolerating high organic load and biogas production.

Even though anaerobic digestion can serve as an alternative to manure disposal in landfill sites, however, the low carbon to nitrogen (C/N) ratio in animal manures cannot fully satisfy the anaerobic digestion requirements. Hence to conduct an effective anaerobic digestion, there should be another carbon-rich substrate to be co-digested with manure to compensate its carbon deficiency and improve its characteristics for anaerobic digestion. Anaerobic digestion for production of biogas is not a novel process; for many years the process was conducted in Asia; historians claim that the biogas production was performed in Assyria and Persia years before Christ [5]. It is interesting to note that in old days even anaerobic co-digestion was conducted without any knowledge about the effect of addition of carbon-rich substrates to anaerobic digesters by discharging fruit wastes to digesters. The characteristics of co-substrate utilized for co-digestion is important; wastes with high carbon and low nitrogen contents are favored. Among different feedstocks potent to be used as co-substrate in anaerobic digestion, lignocellulosic residues seem promising as they are rich in carbon and abundantly available at low cost. The intricate composition of lignocellulosic materials, where cellulose fiber is tightly linked to hemicellulose and lignin, hinders their biodegradability and thus restricts their use as the sole substrate for anaerobic digestion [6]; however, through co-digestion with manure, they can be converted to valuable products and contribute to waste to energy plants. A scheme of anaerobic co-digestion plant in which manure and lignocellulosic wastes are co-digested to provide energy and fuel is illustrated in Fig. 1.

As any process, anaerobic digestion has its own advantages and drawbacks. Long retention time for digestion and low heating value of the produced gas are considered as the main disadvantages associated with this process. Most studies on anaerobic co-digestion are concerned with enhancement of biogas production while increasing methane content and shortening the retention time to increase the treatment capacity of the unit. Nevertheless, for today's demand the old anaerobic digestion systems with low efficiency are not efficient anymore. Recent researches have shown that combination of modern reactors and optimized digestion conditions can reduce the hydraulic retention time (HRT) and enhance methane and biogas production yields.

This paper provides a review on co-digestion of animal manures and lignocellulosic biomass residues for biogas production as an evolving field of sustainability. It is obvious that the anaerobic digestion of manure reduces the emission of CH_4 from manure, however, the amount of carbon being mineralized to biogas and utilized in the plants, instead of being released into the atmosphere depends on the reaction condition. Here, an outline of the most effective parameters on the performance and stability of anaerobic co-digestion process which include temperature, pH, OLR, HRT, C/N ratio, alkalinity and concentrations of VFA is presented and different findings and conclusions from the literature are reviewed. Moreover, different methods used for the pretreatment of substrates to enhance their digestibility are discussed. An overview of the most influential inhibitors which can disturb the anaerobic digestion or even cease the process is presented and at the end the strategies used for upgrading the produced biogas are reviewed.

2. Anaerobic digestion

Basically, anaerobic digestion is characterized by reaction wherein, biogas is produced from biodegradable materials under anaerobic condition. Composition of the produced biogas depends on the utilized substrate and digestion conditions. Biogas is mostly comprised of methane and carbon dioxide, with minor amounts of other gases including nitrogen, hydrogen, hydrogen sulfide, ammonia and water vapor. The evolution of biogas occurs through the activity of various microorganisms in three steps; namely, hydrolysis, acidogenesis (also called fermentation) and methanogenesis [7,8]. Although some references describe the progression of anaerobic digestion within four steps including hydrolysis, acidogenesis, acetogenesis and methnogenesis [9]. A microbial consortium comprising of different species of hydrolytic organisms, acidogens and methanogens are known to be responsible for biogas production. Fig. 2 depicts a scheme of the steps involved in anaerobic digestion.

In the hydrolysis step, complex materials such as lipids, polysaccharides, proteins and nucleic acids are converted to soluble compounds including fatty acids, monosaccharides, amino acids, purines and pyrimidines. In the next step (fermentation), acetate, hydrogen, carbon dioxide, formate, methanol, methylamines, propionate, butyrate, etc. are produced by acidogenesis. At the final stage, methane is produced by two groups of methanogens; i.e., acetoclastic (acetate consumer) and hydrogen-utilizing methanogens (H_2/CO_2 consumer). Acetoclastic methanogens split acetate into methane and carbon dioxide, while hydrogen-utilizing methanogens are responsible for methane production using CO_2 and hydrogen as electron acceptor and donor, respectively. Synthesis of methane from different precursors is summarized in Reactions (1)–(6) [7,10]:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \quad (1)$$

$$4HCOO^- + 4H^+ \rightarrow CH_4 + 3CO_2 + 2H_2O \quad (2)$$

$$4CO + 2H_2O \rightarrow CH_4 + 3CO_2 \quad (3)$$

$$4CH_3OH \rightarrow 3CH_4 + CO_2 + 2H_2O \quad (4)$$

$$4(CH_3)_3N + 6H_2O \rightarrow 9CH_4 + 3CO_2 + 4NH_3 \quad (5)$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (6)$$

The organisms responsible for the hydrolysis and acidogenesis are facultative and obligate anaerobic bacteria. Isolation of several bacterial genera including *Clostridium, Peptococcus, Bifidobacterium, Desulphovibrio, Corynebacterium, Lactobacillus, Actinomyces, Staphylococcus* and *Escherichia coli* from anaerobic digesters has been reported [6,7,11]. As mentioned, methane production is conducted by two groups of methanogens; the community composition of methanogens is similar to microbial consortium of ruminant animal's stomach. *Methanobacterium*, *Methanobacillus*, *Methanococcus*, *Methanothrix* and *Methanosarcina* are the main microorganisms which serve for methane production in the anaerobic digestion [7,12]. All of the methanogens are archaea and strict obligate anaerobes which require redox potentials below −300 mV for growth [13]. They are very sensitive to oxygen and grow very well in the presence of H_2 and CO_2. *Methanosarcina* and *Methanothrix* are among the limited