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Intensification of biogas production using pretreatment based on hydrodynamic cavitation

Pankaj N. Patil [a], Parag R. Gogate [a], Levente Csoka [b,*], Agota Dregelyi-Kiss [c], Miklos Horvath [c]

[a] Department of Chemical Engineering, Institute of Chemical Technology, Mumbai 400 019, India
[b] University of West Hungary, Institute of Wood Based Products and Technologies, 9400 Sopron, Hungary
[c] Obuda University, Donat Banki Faculty of Mechanical and Safety Engineering, 1081 Budapest, Hungary

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ABSTRACT

The present work investigates the application of hydrodynamic cavitation (HC) for the pretreatment of wheat straw with an objective of enhancing the biogas production. The hydrodynamic cavitation reactor is based on a stator and rotor assembly. The effect of three different speeds of rotor (2300, 2500, 2700 rpm), wheat straw to water ratios (0.5%, 1% and 1.5% wt/wt) and also treatment times as 2, 4 and 6 min have been investigated in the work using the design of experiments (DOE) approach. It was observed that the methane yield of 31.8 ml was obtained with untreated wheat straw whereas 77.9 ml was obtained with HC pre-treated wheat straw confirming the favourable changes during the pre-treatment. The combined pre-treatment using KOH and HC gave maximum yield of biogas as 172.3 ml. Overall, it has been established that significant enhancement in the biogas production can be obtained due to the pretreatment using HC which can also be further intensified by combination with chemical treatment.

1. Introduction

Conventional sources of energy like fossil fuels and oil are depleting at a very fast rate imparting the need of developing alternate sources of energy. Biogas, a clean and renewable source of energy, can be a good substitute for the conventional sources of energy. Biogas can be produced using different approaches and one of the sustainable approaches is based on the use of waste lignocellulosic biomass including the agricultural residues which is of considerable importance to the agriculturally dominated countries like India. Wheat is grown in significant amounts in most of the Indian, European and Chinese regions and after the main harvesting, remaining straw offers a lucrative source of biomass to be used for biogas production. Anaerobic digestion is the commonly employed approach worldwide for commercial production of biogas from organic materials including sustainable biomass. Anaerobic digestion is a biological method, typically including four steps, in which organic material is disintegrated by a variety of microbes under oxygen free conditions resulting into the production of biogas [1–3]. In the first step of the process, the extracellular enzymes produced by hydrolytic microbes hydrolyse the complex organic polymers to simple soluble monomers. In this step, proteins, lipids, and carbohydrates are typically hydrolysed to amino acids, long-chain fatty acids, and sugars, respectively. In the next step, these small molecules are converted by the fermentative bacteria to a mixture of volatile fatty acids and other minor products such as alcohol. In third step of the process, acetogenic bacteria convert the volatile fatty acids to acetate, carbon dioxide, and/or hydrogen, which provide direct substrates for methanogenesis, which is the last step resulting in the production of biogas [4]. Methanogenesis is commonly considered to be the rate-limiting step in the anaerobic digestion as methanogens are believed to have slowest growth rate [5]. However, for the degradation of lignocellulosic biomass, hydrolysis is more commonly observed to be the rate limiting step [6] especially when refractory biomass such as waste residues is used.

Lignocellulosic biomass like wheat straw mainly consists of three types of polymers, namely cellulose, hemicellulose, and lignin. The carbohydrate components i.e. cellulose and hemicellulose are fermentable after hydrolysis, which makes lignocellulosic biomass a suitable feedstock for biogas production. But, the inherent characteristics of native lignocellulosic biomass, like structural and chemical properties, make it resistant to biodegradation by enzymes and microbes. Wheat straw pre-treatment earlier to anaerobic digestion is generally required to reduce the structural and compositional barriers present in the lignocellulosic biomass and expose the polymer chains of cellulose and hemicellulose to

* Corresponding author.
E-mail address: levente.csoka@skk.nyme.hu (L. Csoka).

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microbial breakdown so as to enhance the rate of biomass degradation and biogas yield. Because of the complexity and inconsistency of biomass chemical structures, the optimal pre-treatment method and conditions depend on the type of lignocellulosic materials used for processing and cannot be generalised.

Pre-treatment methods can be broadly classified into three types namely physical, chemical and biological. Physical pre-treatment approaches do not use any chemicals or microorganisms and includes techniques like comminution [7,8], liquid hot water pre-treatment [9], steam-explosion [10,11], irradiation [12,13] and extrusion [14]. In the case of liquid hot water pre-treatment, pressure is used to keep water in the liquid state at higher temperatures. Biomass experiences high temperature cooking in water at a high pressure and water can enter into the biomass cell structure, hydrating cellulose, solubilising hemicellulose, and to some extent removing lignin [15,16]. In steam explosion method, biomass particles are heated with high-pressure saturated steam for a short period of time and the pressure is rapidly reduced to stop the reactions, due to which the biomass experiences an explosive decompression. Steam-explosion was reported to be an efficient technology for increasing methane yield from wheat straw by 20–30%, as compared to untreated wheat straw [17]. Irradiation methods are based on the use of microwave, gamma-ray, and electron beam treatment. Jackowiak et al. [18] investigated the optimisation of a microwave pre-treatment of wheat straw for methane production and reported about 30% enhancement in the methane yield as compared to untreated wheat straw. Extrusion is another physical pre-treatment process where biomass is fed into one end of the extruder and transported along the length of the barrel with a driving screw. By means of the material passages along the barrel, it is exposed to friction and vigorous shearing upon pressure release at the finishing end [19] giving structural changes in the processed straw enabling easy digestion in the subsequent step.

Chemical pre-treatment refers to the usage of chemicals, like acids [20,21], bases [22,23], and ionic liquids [24] for alteration of the physical and chemical characteristics of lignocellulosic biomass. Due to the use of chemicals, this may not be a preferred approach for sustainable processing. Biological pre-treatment for improvement of biogas production in anaerobic digestion has primarily focused on fungal pre-treatment [25], pre-treatment by microbial consortium [26], and enzymatic pre-treatment [10]. Biological approaches, though sustainable, are often criticised by the slowness of the process and significant costs associated with the enzymes. A critical analysis of these pre-treatment approaches directs that, while different biomass pre-treatment techniques have been reported, each of the approaches have limitations as use of toxic chemicals, significant treatment times, requirement of very high temperatures and pressures or the energy intensive operations. It is thus very important to develop energy efficient as well as cost efficient pretreatment technique, which can be applied for the intensification of the biogas production. Cavitation, generated using ultrasound or hydrodynamic cavitation also offers promise for intensification of different physical and chemical processing applications [27]. Cavitation can be produced by passage of ultrasonic waves through the liquid medium (acoustic cavitation) or by making use of the alternations in the liquid flow in the hydraulic systems (hydrodynamic cavitation). Ultrasound induced cavitation has been generally applied for intensification of sludge digestion and also for biogas production [28–30] though the use of hydrodynamic cavitation has not been significantly investigated. This is despite the fact that hydrodynamic cavitation offers energy efficiency way of achieving physicochemical transformations [31,32]. Some of the earlier studies dealing with application of hydrodynamic cavitation for treatment of lignocellulosic materials include delignification of wheat straw for paper manufacturing [33] and delignification of wood to obtain cellulosic pulp fibres [34]. The present work reports the use of hydrodynamic cavitation for intensification of biogas production based on the pretreatment of sustainable biomass. Structural and chemical properties of biomass make it resistant to biodegradation by microbes. The collapse of the cavities in the case of hydrodynamic cavitation, results in release of large magnitudes of energy which helps in dissolution of lignin in biomass and make it more suitable for subsequent bacterial decomposition possibly giving in higher yields of biogas during the anaerobic digestion process. Milled wheat straw is used as the sustainable substrate for the biogas generation. There have been no earlier studies related to the use of hydrodynamic cavitation and hence this forms the novel aspect of the current work. In the case of pretreatment using hydrodynamic cavitation, the main energy consuming part is only the motor used for rotation of the rotor. So the operating cost is associated with only electricity consumption by the motor which is relatively low and can be negligible compared to the extra biogas and methane yields that can be obtained. KOH chemical costs contributes in some extent, but compared to the reduction that can be obtained due to the use of waste agricultural straw, overall it has no significant contribution to the pretreatment cost.

2. Materials and methods

2.1. Materials

Milled wheat straw (finely chopped) with size over the range of 0.125–1 mm was used for the experimental investigations. Initially wheat straw was chopped to 5 mm length using standard straw chopper and then it was again chopped and screened to a size of 0.125–1 mm. Industrial sludge was obtained from South-Pest Wastewater Treatment Plant, Budapest, Hungary, which is typically developed for the treatment of effluents from households. The corresponding COD value of the used domestic sludge was around the standard value, 1 g/ml. The finely chopped wheat straw was pre-treated with the help of hydrodynamic cavitation device and chemical retting.

2.2. Equipments

The hydrodynamic cavitation device used for the generation of cavitation is a stator and rotor assembly. The diameter of the rotor is 19 cm with ratio of diameter to height of the rotor as 1.9 and this rotor is contained in a cylinder with diameter of 21 cm. Gap between the stator and the rotor is fixed at 10 mm. Rotor is attached to a gear assembly, which is connected to a variable frequency drive (VFD). With the help of VFD, the rotor can be rotated at different speeds of rotation in a restricted annular space and chopped straw suspended liquid is passed through the opening between the stator and the rotor. On the surface of the rotor, indentations are provided which are responsible for generation of cavitating conditions. There are a total 204 indentations equidistant from each other. Each indentation is 12 mm in diameter and 20 mm deep. During the passage of liquids through the equipment, the liquid at very high velocities enters to the indentation due to rotary action of the cylinder and when liquid comes out from the indentation due to centrifugal flow, a low pressure region is generated near the upper surface of the indentations which results into cavitation [33]. The schematic representation of experimental setup used for the investigations has been shown in Fig. 1 whereas the schematic of an indentation on the rotor has been given in Fig. 2. The intensity of the cavitational effect and its inception can be established with the cavitation number and the calculations related to the stator-rotor assembly has been presented in our earlier work [35].