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Cavitation based pretreatment of biomass for intensification of biogas production

Swapnil M Mahajan, Sankalp K Salunkhe, Apurva A Mahadik & Sandip H Gharat*
Department of Chemical Engineering, Gharda Institute of Technology, Ratnagiri 415 708, Maharashtra, India
E-mail: sandipgharat78@gmail.com

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Biogas, a clean and renewable form of energy, could very well substitute for conventional sources of energy (fossil fuels, oil, etc.) which are causing environmental problems. The present work investigates the application of hydrodynamic cavitation (HC) for the pretreatment of biomass with the objective of enhancing biogas production. Effect of different parameters viz.rice straw to water ratio (0.5%, 1%, 2%, 3%, and 4%), operating pressure (1-3 bar), and also treatment time (10-30 min) have been investigated using an orifice plate as a cavitating device. The water displacement method is used for the analysis of the quantity of biogas formation. As we increased the biomass ratio is increased from 0.5 to 3% with the same treatment time 15 min biogas yield also increased from 52 to 345 mL respectively. Combining chemical treatment with hydrodynamic cavitation it has been observed that it gives a maximum (470 mL) of biogas yield as compared to HC alone (360 mL) for the same biomass ratio of 4%. Overall, it has been established that a 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.

Keywords: Anaerobic digestion, Biogas, Hydrodynamic cavitation, Intensification, Lignocellulose

In today's energy-demanding lifestyle, the need for exploring and exploiting new sources of energy that are renewable as well as eco-friendly is a must[1]. Biogas, a clean and renewable form of energy, could very well substitute (especially in the rural sector) for conventional sources of energy (fossil fuels, oil, etc.) which are causing ecological–environmental problems and at the same time depleting at a faster rate[1]. Lignocellulosic biomass, such as agricultural residuals and energy crops is an abundant organic resource[2,3]. Large quantities of lignocellulosic residues accumulate from agricultural, forestry, municipal, and other activities[4].

Anaerobic digestion (AD) is a biological process in which organic matter is decomposed by an assortment of microbes under oxygen-free conditions and produces biogas[5]. The AD process can be divided into four steps as shown in. At the beginning of the process, hydrolysis occurs as extracellular enzymes, which are produced by hydrolytic microbes, decompose complex organic polymers into simple soluble monomers[6]. Proteins, lipids, and carbohydrates are hydrolyzed to amino acids, long-chain fatty acids, and sugars, respectively. These smallmolecules are then converted by fermentative bacteria (acetogens) to a mixture of volatile fatty acids (VFAs) and other minor products such as alcohol. Acetogenic bacteria further convert the VFAs to acetate, carbon dioxide, and/or hydrogen, which provide direct substrates for methanogenesis, the last step of the AD process for methane production[4]. Lignocellulosic biomass mainly consists of three types of polymers: cellulose, hemicellulose, and lignin. The carbohydrate components (cellulose and hemicellulose) are fermentable after hydrolysis, which makes lignocellulosic biomass a suitable feedstock for bioenergy production. However, the inherent characteristics of native lignocellulosic biomass, such as structural and chemical properties, make it resistant to biodegradation by enzymes and microbes[4,6]. The properties of lignocellulosic biomass render it resistant to biodegradation. Due to the complexity and variability of biomass chemical structures, the optimal pretreatment method and conditions depend on the types of lignocellulose present[7]. Several structural and compositional properties were found to have impacts on the biodegradability of lignocellulosic biomass, including cellulose crystallinity, accessible surface area, degree of cellulose polymerization, presence of lignin, and hemicellulose To improve these properties pretreatment methods can be broadly classified into three types namely physical, chemical and biological[3,8,9]. Cavitation can be produced by the 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)[10,11].

Hydrodynamic cavitation can simply be generated by the passage of the liquid through a constriction such as a throttling valve, orifice plate, venturi, etc. When a liquid passes through the constriction, the kinetic energy of a liquid increase at the expense of the pressure. If the throttling is sufficient to cause the pressure around the point of vena contracta to fall below the threshold pressure for cavitation (usually vapour pressure of the medium at the operating temperature), millions of cavities are generated. Subsequently, as a liquid jet expands and the pressure recovers, the cavities collapse resulting in the release of large magnitudes of energy, which helps in the dissolution of lignin in biomass and make it more suitable for subsequent bacterial decomposition possibly giving higher yields of biogas during the anaerobic digestion process[5,12].

It is important to develop energy-efficient as well as cost-efficient pre-treatment techniques, which can be applied for the intensification of biogas production[11]. The effects of ultrasonic and microwave sludge pre-treatments on biogas production through the anaerobic co-digestion of wastewater sludges (WAS)[13]. Previous studies showed that Ultrasound-assisted and Microwave pretreatments applied to WAS were effective in the solubilization of organic matter leading to an increased biogas production[14-18]. A review report[19] showed that ultrasonication pretreatment in sludge digestion improved the biogas production by 24 to 138% in batch mesophilic AD while this improvement was 45–79% when the sludge was pre-treated with microwave[20]. Accordingly; Mata-Alvarez *et al.*[19] showed that anaerobic co-digestion can increase CH4 production by 50–200% depending on the operating conditions and co-substrates used.

In the case of pretreatment using hydrodynamic cavitation, the main energy-consuming part is only the motor used for pumping the slurry. 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 yield that can be obtained. KOH chemical costs contribute to 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[10]. The present work investigates the application of hydrodynamic cavitation (HC) for the pretreatment of rice husk with the objective of enhancing biogas production[21].

Experimental Section

Materials

In this experiment, we used rice husk (nearly powder formed) with a husk to water ratio (2%- 3%). We used powder form for avoiding choking at the orifice plate. Industrial wastewater was obtained from the industry in Lote MIDC. The corresponding COD value of the used wastewater was in the range of 10000-12000 ppm. Powder form rice husk was pre-treated with the help of a hydrodynamic cavitation device.

Experiment setup and procedure

For pretreatment method

The hydrodynamic cavitation reactor used in the work (Fig. 1) consists of a reservoir or a collecting tank with a 10 L capacity that is connected to the pump (398 W) which allows re-circulation of the contents through a mainline housing an orifice plate (5 mm diameter of the holes or the orifice plates can be inserted in the mainline) and a bypass line (for controlling the inlet pressure)

For anaerobic digestion

For anaerobic digestion, we used three glass bottle setup as shown in Fig. 2. This glass bottle was sealed with 3 mm silicone sealing at the top and the empty portion in the bottle was filled with nitrogen to take out the oxygen present in the bottle. Second glass bottle containing 500 mL distilled water was subsequently connected to this first bottle with the rubber tubing so that the gas produced in the first

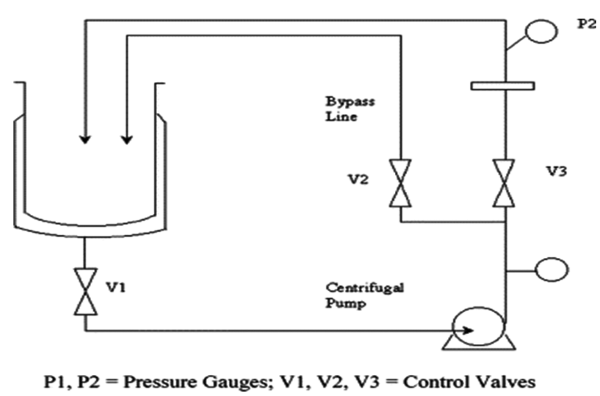

Fig. 1 — Schematic representation of the experimental setup for pretreatment using hydrodynamic cavitation.

bottle will come into the second bottle. The second bottle is connected to the third empty bottle with rubber tubing, through which the displacement of distilled water from the second bottle to the third bottle takes place. Such an arrangement of bottles was made for all the samples pre-treated with hydrodynamic cavitation under different sets of operating parameters. This batch arrangement of three bottles was then placed in the incubator and the temperature was maintained at 37°C. The amount of biogas produced was measured at regular time intervals and methane contents were also analyzed at the same time.

Combination with chemical pretreatment

To study the effect of chemical pre-treatment on the biogas enhancement, the chopped rice husk was retted in an alkaline solution of 0.3 M potassium hydroxide (KOH), water to straw ratio was 12, for 48h for pre-softening of lignin cellulose complex at room temperature. Mixing of this retted pulp was performed every 12 h during the chemical treatment to obtain well-mixed conditions. This retted rice husk was then diluted to 3 wt. % to be able to pump the slurry into the hydrodynamic cavitation reactor (*p*H of the solution also came to about neutral during this dilution) and then treated in a hydrodynamic cavitation device in the same manner as discussed above. This combination approach was also used to check the efficacy of combined chemical/physical treatment approaches.

Results and Discussion

After all the sets of experiments are done, the set-up is kept in the incubator. The yield obtained on the 5th day is anaerobic digestion which is an effective biological process for treating a broad range of biomass feedstocks for low-cost production of biogas. However, AD efficiency is highly dependent on the type of feedstock. For example, the digestion of livestock manure is more efficient than the digestion of lignocellulosic biomass because of the complexity of lignocellulose. Pretreatment can decrease the crystallinity of cellulose, increase accessible surface area, and reduce lignin content, depending on the functioning mode of the pretreatment methods.

It was observed that intensification of biogas production with treated biomass is more as compared to untreated biomass because after pretreatment lignin layer of biomass is the breakdown. It also indicated that the biodegradability of lignocellulosic biomass increased with decreasing lignin content; the higher the lignin content, the lower the biogas production. It is also observed increase in biogas yield is attributed to the reduction in the structural barrier of lignocellulosic biomass because of cavitation Biogas yields in the case of pre-treated rice husk were more as compared to untreated rice husk in all the cases as shown in Fig. 3.

The effect of biomass particle size on the intensification of biogas production was also studied. Reducing the biomass particle size resulted in getting more biogas yield at a faster rate. It is also observed

Fig. 2 — Three bottle arrangement setup.

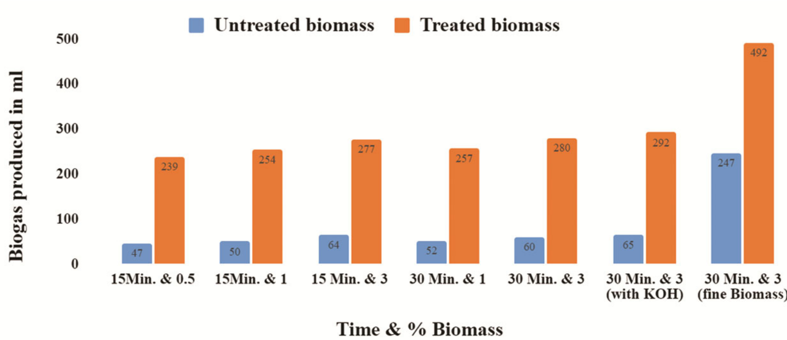

Fig. 3 — Biogas produced at different treatment times and biomass to water ratio

that when we use rice husk in powder form then the rate of intensification of biogas production is more as compared to coarse rice husk. The length of rice husk is 2-5 mm, the coarse particle size range is 1.2 to 1.8 mm, and the fine particle size is 85 to 212-micron

Figure 4 shows a comparison of the yields of biogas obtained with coarse biomass and fine biomass hemicellulose and cellulose. Due to this removal, lignocellulosic biomass becomes more degradable to microbes and enzymes. In the case of combining chemical treatment with hydrodynamic cavitation, KOH solution is used for presorting biomass which makes biomass more accessible for breaking the lignin layer and easy to digest cellulose from the biomass. Also, this method gave the biogas yield within 4 days whereas the pretreatment with only hydrodynamic cavitation took 7 days for complete generation of biogas.

The biomass to water ratio is also one of the important parameters which affect the intensification of biogas production. It was observed that the intensification of biogas production is increased with an increase in biomass to water ratio refer to Table 1.

Figure 5 shows the yield of biogas obtained for different biomass water ratios. And it clearly indicates

Table 1 — Biogas produced at different fine biomass to water ratios with constant treatment time for finebiomass

Sr. No	Treatment Time (min)	Biomass %	Biogas produced (In terms of mL of water displaced)	
			Untreated biomass	Treated biomass
1	15	0.5	36	52
		1	106	144
		2	175	185
		3	125	40
		4	265	345
2	30	2	253	348
		3	260	545
		4	265	360
3	15 (withKOH)	2	180	225
	30 (with KOH)	4	288	470

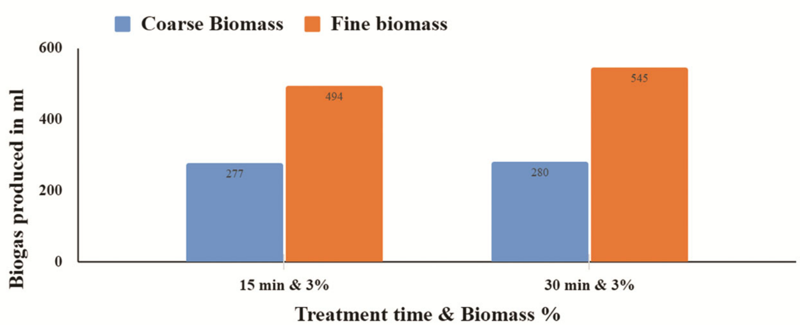

Fig. 4 — Effect of biomass particle size on intensification of biogas production.

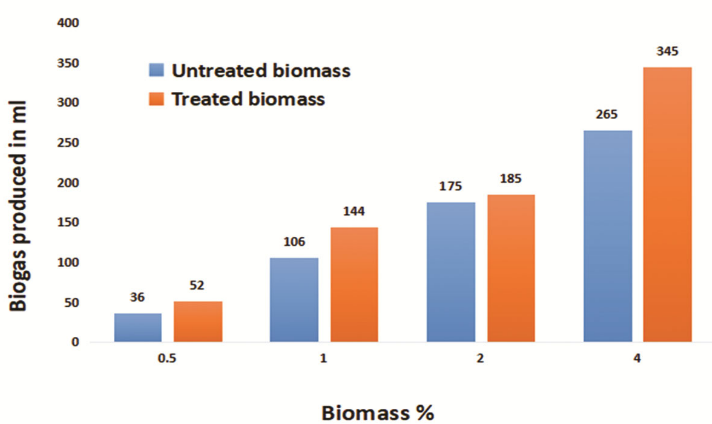

Fig. 5 — Effect of biomass to water ratio on intensification of biogas production.

that as we increase biomass % the yield of biogas also increases, for 0.5% is minimum (52 mL) and 4% is maximum (345 mL). In the case of rice husk to water ratio, it was observed that beyond 4% it was difficult to run the cavitating device because at a higher percentage the clogging was observed in the cavitation chamber. As expected biogas produced in treated biomass is higher than untreated biomass for all ratios of rice husk to water (0.5 to 4%).

Figure 6 shows the yield of biogas obtained for different treatment times (15 and 30 min.) for both coarse and fine biomass. It was observed that for the same biomass to water ratio (1%) with different treatment time intervals as 15 min and 30 min the yield of biogas obtained 254 mL and 257 mL respectively and similarly to the other two results. From there it was observed that there is no more effect of treatment time on biogas production. Alkaline pretreatment using bases such as KOH also intensifies the removal of lignin, hemicellulose, and cellulose. Due to this removal, lignocellulosic biomass becomes more degradable to microbes and enzymes. In the case of combining chemical treatment with hydrodynamic cavitation, KOH solution is used for presorting biomass which makes biomass more accessible for breaking the lignin layer and easy to digest cellulose from the biomass. Also, this method gave the biogas yield within 4 days whereas the pretreatment with only hydrodynamic cavitation took 7 days for complete generation of biogas.

Figure 7 shows a comparison of the yields of biogas obtained with the combination of KOH with hydrodynamic cavitation and hydrodynamic cavitation alone for the pre-treatment of rice husk. Intensification of biogas production with a combination of KOH and hydrodynamic cavitation gave a 470 mL biogas yield which is more than the hydrodynamic cavitation alone 360 mL because of the pre-pre-softening process. It was observed that the KOH with HCL gave results at a faster rate as compared to hydrodynamic cavitation alone. Alkaline pretreatment helps in loosening the complex structure

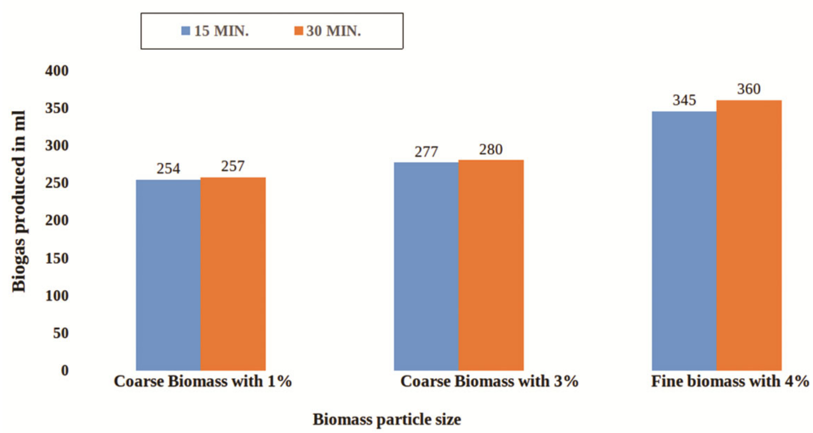

Fig. 6 — Effect of treatment time on intensification of biogas production

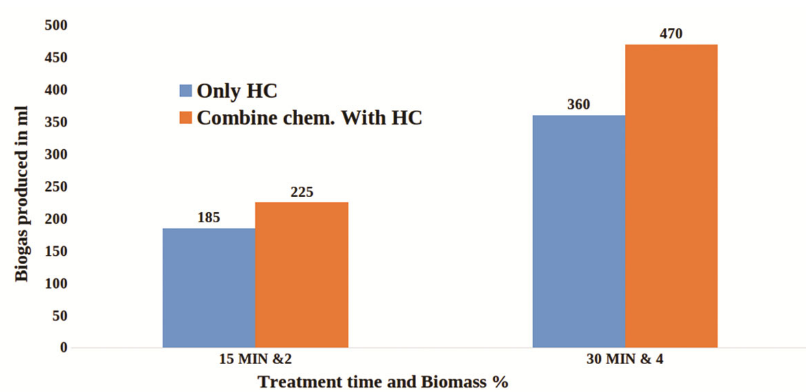

Fig. 7 — Effect of combined chemical treatment with hydrodynamic cavitation on intensification of biogas production.

of polysaccharides of lignocellulosic biomass and enhances biogas production via anaerobic digestion.

Conclusion

Overall, significant enhancement in biogas production has been obtained on the basis of pretreatment using cavitation.

Hydrodynamic cavitation provided a promising approach that was applied for increasing the anaerobic digestion efficiency of lignocellulosic biomass like rice husk. Intensification of Biogas production increased with treated biomass (277 mL) as compared to untreated biomass (64 mL).

As we increase the biomass ratio the rate of biogas production also increases. Increase in biomass ratio from 0.5 to 3% with same treatment time 15 min biogas yield also increases from 52 to 345 mL respectively because.

As the treatment time is increased the intensification of biogas production is not considerably higher, for different treatment times 15 and 30 min with the same biomass ratio (4%) it gave 345 and 360 mL of biogas yield respectively.

Reducing the biomass particle size resulted in getting more biogas yield at a faster rate (In the case of finely treated biomass, the yield of biogas obtained 545 mL which is more than the coarse treated biomass which is 280 mL).

The combination of chemical treatment with HC gives more biogas yield (470 mL) than the hydrodynamic cavitation alone (360 mL) because of the pre-pre-softening process. It was observed that the KOH with HCL gave results at a faster rate as compared to hydrodynamic cavitation alone.

It is evident that as we increased the amount of biomass in water, the yield of biomass increased considerably. This is just a lab-scale measurement. The amount is only 400 mL. Hence, if this technique is applied at the industrial level, a huge amount of biogas can be produced. In this way, we have achieved two targets i.e. the treatment of industrial wastewater and the production of biogas which is our key interest.

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