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Research article

Improvement of ethanol and biogas production from sugarcane bagasse using sodium alkaline pretreatments

Mohammad Javad Nosratpour[a], Keikhosro Karimi[a,b,*], Morteza Sadeghi[a]

[a] Department of Chemical Engineering, Isfahan University of Technology, Isfahan, 84156-83111, Iran
[b] Industrial Biotechnology Group, Research Institute for Biotechnology and Bioengineering, Isfahan University of Technology, Isfahan, 84156-83111, Iran

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ABSTRACT

Sugarcane bagasse was pretreated with sodium carbonate, sodium sulfite, and sodium acetate in concentrations of 0.5 M and 0.25 M, as well as hydrothermal pretreatment, to break down its structural recalcitrance and improve biogas and ethanol production. The pretreatments were conducted at 100, 140, and 180 °C for 1 h. The highest biogas and ethanol production was observed for sugarcane bagasse pretreated with 0.5 M sodium carbonate solution at 140 °C, which was 239 ± 20 Nml CH_4/g VS, and 7.27 ± 0.70 g/l, respectively, containing gasoline equivalents of 164.2 ± 14.3 l/ton of raw bagasse and 147.8 ± 14.2 l/ton of raw bagasse, respectively. The highest gasoline equivalent was obtained for biogas production from the substrate pretreated with 0.5 M sodium sulfite solution at 100 °C (190.2 ± 2.1 l/ton of raw bagasse). In comparison to sodium carbonate and sodium sulfite, sodium acetate had less effect on biofuel production and was comparable with hydrothermal pretreatment. In contradiction to sodium acetate pretreated bagasse, in which increased pretreatment temperature intensified biofuel production, a reduction of biofuel production was observed for sodium carbonate and sodium sulfite pretreatment when temperature was increased from 140 to 180 °C. Besides considerable amounts of biofuel production at the best conditions obtained, over 762 and 543 kilotons of equivalent CO_2 can be reduced annually in Iran by biogas and ethanol production from sugarcane, respectively.

1. Introduction

Today, energy supply and environment pollution are the two most important concerns of human societies worldwide (Chandra et al., 2012; Jabłoński et al., 2017; Milano et al., 2016). Based on predictions, the current sources of energy, which are mostly non-renewable, will serve for not more than the few next decades (Guo et al., 2015). Thus, investigation for new sources of energy, i.e., renewable energies, is imperative. Among the different renewable sources, biofuels, e.g., ethanol and biogas, are the most promising alternatives. Predictions indicated that by 2050, the production of biofuels will increase to four-fold, reducing the CO_2 emissions by 50% (Mohapatra et al., 2017).

Anaerobic digestion is one of the biofuel production processes that receives considerable attention. It is among the cost-effective and competitive processes to reduce greenhouse gas emissions from digestible waste materials. The final product of this process is biomethane, which is a clean fuel, primarily used for heat and electricity production (Alexandropoulou et al., 2017).

Nowadays, ethanol is used worldwide as a fuel or fuel additive (Victor et al., 2015). It is mainly produced from starch or sugar-based substrates. Brazil and the USA, respectively produce over 28 (Rivera et al., 2017) and 58 million m^3 (USEIA, 2018) of ethanol annually. However, the production of ethanol from current resources always has conflicted with food resources, and further production from the latter is almost impracticable (Chakravorty et al., 2015; Liu et al., 2017).

Lignocelluloses, which are other renewable sources for biofuel production, are widely available and inexpensive with no conflict with food security (Hashemi et al., 2016; Klein et al., 2016). The main sources of lignocelluloses are forestry wastes and agriculture residues.

Sugarcane plant is cultivated in many areas for sugar production and its major by-product is bagasse (Sindhu et al., 2016). Sugarcane bagasse, the lignocellulosic residue remaining after the extraction of sugarcane juice, is one of the most abundant agriculture residues. Sugarcane bagasse production exceeds 540 million tons per year globally (Zhao et al., 2015). Approximately 0.3 ton of sugarcane bagasse is produced per ton of sugarcane harvested (Soetaert and Vandamme, 2009). Bagasse has great potential for second-generation biofuel production and has recently received much attention (Neves et al., 2016; Ojeda et al., 2011; Rabelo et al., 2011; Soccol et al., 2010).

Lignocelluloses are composed of different carbohydrates, i.e.,

* Corresponding author. Department of Chemical Engineering, Isfahan University of Technology, Isfahan, 84156-83111, Iran.
E-mail address: karimi@cc.iut.ac.ir (K. Karimi).

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cellulose and hemicellulose, which have the potential to be converted to simple sugars and subsequently used for the production of different biofuels. However, they have recalcitrant and complex structures with limited access for microorganisms and enzymes. Therefore, a pretreatment process is necessary for the efficient conversion of lignocelluloses for biofuel production. Pretreatment can reduce crystallinity and the degree of polymerization of cellulose, remove lignin and hemicellulose, and increase the accessible area for hydrolytic enzymes and microorganisms (Taherzadeh and Karimi, 2008).

Different pretreatments have been presented and divided into physical, chemical, and biological pretreatments. However, most of the pretreatment processes are costly and investigation for inexpensive and eco-friendly processes still continues.

Among these processes, alkaline pretreatment has high efficiency on lignocelluloses, especially agricultural residues (Shafiei et al., 2015). Sodium hydroxide is the most common agent for alkaline pretreatment, and more recently application of sodium carbonate (Na_2CO_3) and sodium sulfite (Na_2SO_3) was suggested (Yang et al., 2013).

Khaleghian et al. (2015) used mild sodium carbonate pretreatment on rice straw. Under the best conditions, enzymatic hydrolysis yield was increased from 35% to 100% by pretreatment with 0.5 M sodium carbonate at 100 °C for 3 h. Mirmohamadsadeghi et al. (2016) pretreated stover, miscanthus, and switchgrass with sodium carbonate and obtained high glucose yields of 95.1%, 62.3%, and 81.3%, respectively. The pretreatment removed 40–59% lignin while retaining more than 95% of cellulose. Hashemi et al. (2016) applied sodium carbonate for the pretreatment of safflower straw. They showed that ethanol yield increased from 11.1% for raw safflower straw to 58.1% for the substrate pretreated at 180 °C with 1 M Na_2CO_3 for 2 h. The best result for biogas production was 139.6 Nml/gVS after pretreatment at 120 °C with 0.5 M Na_2CO_3 for 1 h, which is quite different from the best conditions for efficient ethanol production.

Yang et al. (2013) used mixtures of sodium carbonate and sodium sulfite to enhance the enzymatic hydrolysis of rice straw. They found that pretreatment at 140 °C with chemical charge of 12% sodium sulfite in the absence of sodium carbonate resulted in the highest sugar recovery.

The aim of this study was to recover high amounts of energy in the form of ethanol and biomethane from sugarcane bagasse. Sodium carbonate, sodium sulfite, and sodium acetate in different concentrations and pretreatment temperatures were used to improve the biofuel production. For the first time, sodium acetate was used for the pretreatment of sugarcane bagasse. Morphological and structural changes occurred through pretreatment were monitored through different analyses. Equivalent gasoline was calculated for all pretreatment conditions to compare their efficiency for energy production and also CO_2 emission reductions was estimated.

2. Materials and methods

2.1. Raw material

Sugarcane bagasse was provided from Dabal Khazaee, a subsidiary of Sugarcane & Affiliated Industries Development Co., Khuzestan Province, Iran, and dried for 5 days away from direct sun radiation at ambient temperature. The bagasse was then ground using a grinder (Model #565, Infinity Conical Burr Grinder, JURA Inc., China) and screened to achieve particle sizes less than 0.85 mm and more than 0.15 mm, using 20 and 80 meshes (DG Scientific Products Co., Iran). The raw material was kept in sealed plastic bags at ambient temperature until use (Satari et al., 2015).

2.2. Pretreatment

Sodium carbonate (Na_2CO_3), sodium sulfite (Na_2SO_3), and sodium acetate (CH_3COONa) solutions at concentrations of 0.5 M and 0.25 M and temperatures of 100, 140 and 180 °C were used. In addition, hydrothermal pretreatment, i.e., pretreatment with water without any chemical, was conducted at the same temperature conditions. All pretreatments were performed in a high-pressure reactor (Keyhan Steel Sanat, Isfahan, Iran) equipped with a pressure indicator and a thermometer (Amiri et al., 2010). In each pretreatment, the reactor was loaded with 20 g sugarcane bagasse (based on dry weight) and 240 mL of pretreatment agent and heated in an oil bath (Memmert GmbH and Co., Germany). It took about 20 min to reach the desired temperature and after that, the mixture was kept at that temperature for an hour. The reactor was manually shaken every 20 min in the oil bath. After finishing the pretreatment, the reactor was cooled in a cold-water bath. Solid and liquid fraction of pretreatments was separated using cotton fabric bags as filter. Next, the solid fraction was washed with tap water until neutralized, and then freeze-dried and kept in sealed plastic bags at ambient temperature for further investigations.

2.3. Enzymatic hydrolysis

The hydrolysis of treated and untreated bagasse was performed in 118 mL glass bottles, sealed with rubber septum and aluminum cap, in a shaker incubator at 120 rpm and 45 °C for 72 h. At first, 0.5 g substrate (dry basis) was added to 20 ml of sodium citrate buffer at pH 4.8 (Selig et al., 2008). Then, 10 FPU per g dry substrate of Cellic® CTec2, kindly provided by Novozymes (Denmark), was added to each bottle (Hashemi et al., 2016). The activity of the enzyme was 114.8 FPU/ml, as determined by the Adney and Baker (1996) method. Sodium azide, as an antibacterial agent, at the concentration of 0.5 g/l was also added to each bottle (Noori and Karimi, 2016). Liquid samples were taken after 72 h of hydrolysis and analyzed for sugar analysis. The yield of glucose was calculated according to Eq. (1) (Hashemi et al., 2016):

$$Glucose\ yield = \frac{Glucose\ produced\left(g/l\right)}{1.111 \times Glucan\ in\ sample\left(g/l\right)} \quad (1)$$

where the conversion factor of 1.111 was used for glucan hydration to glucose. Enzymatic hydrolyses were conducted in duplicates.

2.4. Ethanol production by simultaneous saccharification and fermentation

Simultaneous saccharification and fermentation (SSF) at 37 °C and 130 rpm under anaerobic conditions for 72 h was used for ethanol production from pretreated and untreated bagasse. A fermentation medium containing 5 g/l yeast extract, 3.5 g/l K_2HPO_4, 7.5 g/l $(NH_4)_2SO_4$, 0.75 g/l $MgSO_4{\cdot}7H_2O$, 1 g/l $CaCl_2{\cdot}2H_2O$, and 25 g/l of either treated or untreated bagasse was used in 50 mM citrate buffer (Bateni and Karimi, 2016). The solution's pH was adjusted to 5 using 2 M NaOH, and the bottle was autoclaved at 121 °C for 20 min. Then, the bottle was cooled to room temperature in a biosafety cabinet, and 1 g/l (based on dry weight) *Saccharomyces cerevisiae* (CCUG 53310, Culture Collection, University of Gothenburg, Sweden) and the 10 FPU enzyme per g dry substrate were added to each bottle. Liquid samples were taken after 72 h for sugar and metabolites analyses (Karimi et al., 2006). All fermentations were duplicated and ethanol yield was calculated by Eq. (2):

$$Ethanol\ yield = \frac{Ethanol\ produced\left(g/l\right)}{Glucan\,(\%) \times 0.51 \times 1.111 \times 25\left(g/l\right)} \quad (2)$$

where 1.111 was the hydration factor of glucan to glucose.

2.5. Biogas production

Anaerobic digestion was done on the treated and untreated substrates. The inoculum was obtained from a 7000 m^3 anaerobic digester