Fuel 218 (2018) 41–48

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Enhancing energy production from waste textile by hydrolysis of synthetic parts

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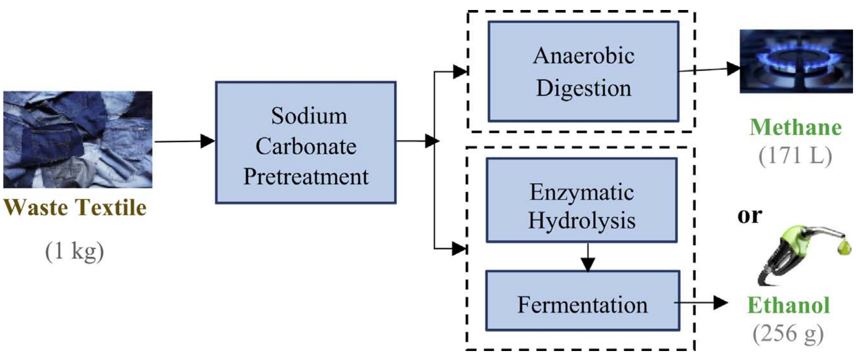
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Biogas
Cotton
Enzymatic hydrolysis
Sodium carbonate
Textile

ABSTRACT

Waste jeans, containing cotton and polyester, are among the widely available sources for bioenergy production. In this study, the cotton part of waste jean was used for biogas and ethanol production. The hydrolysis of non-cellulosic part, i.e., polyester, and the pretreatment of cellulosic part was performed by sodium carbonate treatment. The effects of Na_2CO_3 concentration (0, 0.5, and 1 M) and temperature (50, 100, and 150 °C) on the cotton, polyester, and textile structure were investigated. The pretreated textile, with over 90% cellulose, was subjected to anaerobic digestion, enzymatic hydrolysis, and fermentation to produce biogas, sugars, and ethanol, respectively. The maximum methane yields of 328.9 and 361.1 mL/g VS were achieved from pure cotton and jeans after pretreatment with 0.5 M Na_2CO_3 at 150 °C for 120 min, respectively. Using the pretreatment, the highest glucose yields of enzymatic hydrolysis were 88.0% and 81.71% for cotton and textile, respectively, while the corresponding values for untreated samples were 36.9 and 28.0%. The maximum ethanol yields of 69.4% and 59.5% were obtained from cotton and textile, respectively. It was concluded that the pretreatment is promising for the hydrolysis of the synthetic polymer of textile and the improvement of the biodegradability of the cellulosic part with negligible cellulose destruction.

1. Introduction

Population growth and promotion of living standards have always been one of the key drives to more energy demand and fiber consumption. The fibers are widely used in various aspects of human life, e.g., clothing, furniture, and related industries. At the end of their

Abbreviations: CI, crystallinity index; NMMO, N-methylmorpholine-N-oxide; SNK, student-Newman-Keuls; TCI, total crystallinity index; WBJ, waste blue jeans

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https://doi.org/10.1016/j.fuel.2018.01.035
Received 27 September 2017; Received in revised form 4 January 2018; Accepted 9 January 2018

functional lifetime, they are thrown away as none compostable wastes, which remain as pollutants for a few hundred years [1–3]. According to EPA report (2013), 15.1 million tons of waste textile is generated in the US municipal waste stream annually, which amounts for 6% of the total generation of municipal solid waste [4]. Today, the waste textile management includes reusing as second-hand textiles, reusing as filling materials in the textile industry, composting, landfilling, and burning [5–7]. However, all of these processes have their own environmental impact and lead to the loss of energy and raw materials [8,9]. On the other hand, these wastes have a high potential to be used in the production of valuable products [10]. Polyester/cotton textiles are the most widely available types of textiles, in which their cotton fibers can be used as a feedstock for generating biofuels, e.g., ethanol and biogas, and other value-added products [11]. Similar to lignocellulosic materials, cotton fibers, accounted for around 35% of world fiber use in 2008 [12], are rich in cellulose (more than 88%) [13].

The waste textiles biodegradation, in contrast to lignocelluloses biodegradation, does not face the problems caused by lignin and hemicellulose presence, while the major obstacle is the very high crystallinity of cellulose in the cotton fibers.

Ethanol is an environmentally friendly liquid fuel that can be produced by the fermentation of hydrolysates from cotton-based waste textiles. Biogas is another renewable source of fuel produced through the anaerobic digestion of organic substrates. Methane, the main constituent of biogas (50–70%), offers significant preference over the current forms of energy. Moreover, solid leftover of anaerobic digestion is a nutrient-rich product that is an appropriate substitute for mineral fertilizer with high advantages [13].

One of the main challenges in biofuel production from waste textiles is highly compact and crystalline structure of cotton, resulting in very low bioconversion rate and yield. Thus, an appropriate pretreatment method is required to improve the digestibility of cotton-based waste textiles and achieve a high yield of biogas or ethanol production [10,14,15]. Pretreatments with N-methylmorpholine-N-oxide (NMMO), phosphoric acid, and NaOH have been previously studied, resulting in the cotton crystallinity reduction [10,14,16]. Cotton fibers are more stable in alkali solutions than in acidic solutions. Therefore, alkaline media, e.g., NaOH, Na_2CO_3, and phosphates solutions, are commonly applied in removing the impurities, mercerization, and other processes for the preparation of cotton fiber in the textile industry. Mercerization is an alkaline pretreatment where sodium hydroxide is used that gives the cotton fiber a swollen appearance with silky luster and causes a major change in the crystalline structure of cellulose [17]. Transforming cellulose I, the native form of cellulose with parallel cellulose chains in a unit cell, to cellulose II, the regenerated form of cellulose with an antiparallel direction of cellulose chains in a unit cell, during the pretreatment of cotton fiber with NaOH is reported as an effective method for the improvement of anaerobic digestion of cotton fibers [16]. However, this alkaline treatment has some negative side effects, including corrosion problems and need for neutralization that produces severe environmental pollutant. Considering the high energy consumption, high operating cost for chemical recovery, corrosive properties of acid and alkaline media, and the production of hazardous materials, these methods are impractical for commercial pretreatment purposes. On the other hand, sodium carbonate is a low-cost and environmentally friendly chemical with no or negligible destructive effects on cellulose [18]. Pretreatment with sodium carbonate is one of the promising methods for lignocelluloses bioconversion [19]. The pretreatment with this chemical leads to a significant improvement in the hydrolysis yield of carbohydrates in different lignocelluloses (e.g., rice straw [18,20] and corn stover [21]). The pretreatment with sodium carbonate significantly reduces the cellulose crystallinity of the lignocelluloses [21]. However, to our knowledge, this method was not yet assessed for the improvement of bioconversion of cotton based-waste.

An attempt was made here to improve the bioconversion of cotton based-waste textile by sodium carbonate pretreatment in a high-pressure reactor. Enzymatic hydrolysis followed by fermentation was conducted for ethanol production. Anaerobic digestion was performed for the textile to assess whether methane yield can be improved by the pretreatment. Further analyses, including Fourier transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) imaging, were conducted to follow the changes resulted by the pretreatment.

2. Material and methods

2.1. Materials, enzymes, and microorganisms

The chemicals including sodium carbonate were reagent grades, purchased from Sigma–Aldrich. The raw material used in this study was waste blue jeans (WBJ), containing 40/60 polyester/cotton blend, Simin-No factory, Isfahan, Iran. In all experiments, pure cotton of the same manufacturer was used as a reference to assess the impacts of dye and polyester on the bioconversion. Pure polyester fibers (Simin-No factory, Isfahan, Iran), used for making the jeans, were also used as a reference to examine the effects of the pretreatment on the polyester part of the textile. Moreover, an easily digestible form of pure cellulose from the same manufacturer, viscose rayon, which is a regenerated cellulose using sodium hydroxide and carbon disulfide, was evaluated for comparison. To prepare WBJ samples, the jeans were cut into small pieces (about $2 \times 2\,cm^2$). Total solids contents of cotton and WBJ were 98.7 ± 1.3% and 98.5 ± 1.8%, respectively, as obtained by drying at 105 °C to achieve a constant weight.

Two commercial enzymes of cellulose (Celluclast 1.5 L, Novozymes, Denmark) and β-glucosidase (Novozym 188, Novozymes, Denmark) were used for the hydrolysis of cellulose. The cellulase activity was 75 FPU/mL, measured by Adney and Baker [22] procedure, and the β-glucosidase activity was 147 IU/mL, measured by Ximenes et al. [23] method.

Saccharomyces cerevisiae (Golmayeh, Iranmayeh, Iran) was used as the fermenting microorganism for ethanol production. The microbial inoculum used for biogas production was taken from an industrial anaerobic digester, operating at mesophilic temperature (37 °C) (Isfahan Municipal Wastewater Treatment, Isfahan, Iran). After double filtering with a tea screen, the inoculum was poured into a dark glass container as a digester, and anaerobic conditions were applied using nitrogen gas. To avoid producing a high amount of methane from the endogenous material degradation available in the inoculum, the inoculum was kept in an incubator at 37 °C for 7 days before being used for biogas production.

2.2. Pretreatment procedure

A high-pressure stainless steel reactor with 500 mL total volume was used for the pretreatment of the WBJ and cotton samples [16,20]. The reactor was loaded with 190 g sodium carbonate solution and 10 g WBJ or cotton as a substrate. The ranges of pretreatment parameters were selected based on some preliminary experiments and previously optimizations [20,24]. The pretreatments were performed at different temperatures (50, 100, and 150 °C) with various concentrations of sodium carbonate solution (0, 0.5, and 1 M) for 120 min. The reactor was heated to the desired temperature using an oil bath and manually shaken every 15 min. At the end of the processing time, the reactor was immediately cooled in an ice container. Then, the pretreated solid was filtered, rinsed with distilled water to achieve pH 7, dried at room temperature, and kept in resealable bag at room temperature. The remained solid was precisely weighed to calculate the solid recovery from the pretreatment.

2.3. Enzymatic hydrolysis

The untreated and treated WBJ as well as pure cotton were subjected to enzymatic hydrolysis. A mixture with the substrate