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Hydrolysis of Sorghum (Broomcorn) in Diluted Hydrochloric Acid

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A B S T R A C T

Effective conversion of lignocellulosic material as renewable energy source has significant reflection on economic and environmental impact. Diluted acid hydrolysis at optimal condition was used to liberate fermentable sugar. The sorghum stalks, the alkali pretreatment of biomass and hydrolysis in diluted hydrochloric acid were investigated. The hydrolysis reaction was carried out in a 5L reactor. Several process parameters such as reaction temperature (35to 75°C), acid concentration (3to 7% (w/w)) and dry solid material content (3to 7% (w/w)) were studied. The results showed that the optimal reaction conditions were defined at 75°C, acid concentration of 7% and dry solid material content 5% (dry solid). Under the optimal conditions, maximum reducing sugar yield of about 39% (g/g dry solid) was obtained. SEM and FTIR analysis of the solid residues confirmed disruption of the biomass texture and removal of functional groups associated with cellulosic fibers.

1. INTRODUCTION

Intensive utilization of fossil fuel has led to increase in generation of gaseous pollutions which are released into atmosphere. The pollutants caused global warming and defect on human life. The solution to the environmental pollution depends on how to develop and implement environmental friendly technologies which are based on alternative and renewable energy sources. Through the use of renewable energy resources defined as desired solution for an environmentally friendly process [1]. The potential for the use of lignocellulosic materials to bioethanol production is well recognized [2]. This natural and potentially cheap and abundant polymer found as agricultural waste (wheat straw, corn stalks, soybean residues, sugar cane bagasse), industrial waste (pulp and paper industry), forestry residues, municipal solid waste, etc. [3].

Bioethanol is regarded as an ideal supplement and creditable replacement fuel because it combats climate change; also has a positive impact on air quality [4] and fulfills most of the above criteria for an inexhaustible, cheap and renewable fuel [5]. However, first generation

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of ethanol production is based on crop starches (e.g. corn and wheat); which is directly compete with food and fiber production. Unfortunately, it does not significantly diminish greenhouse gas (GHG) emissions [6]. In light of these shortcomings, focus has shifted towards producing ethanol from lignocellulosic material such as agricultural and forestry residues; which is dedicated to energy crops.

Sorghum stalk is a renewable, cheap and widely available resource, which is commonly used as raw material for ethanol production. Sorghum bicolor is used for food, both for animal and ethanol production [7]. The species can be used as a source for making ethanol fuel, and in some environments may be better than maize or sugarcane, as it can grow under harsh conditions[8-10]. The hydrolysis of sorghum straw to produce xylose solutions could be a good alternative used as abundant resource. The hydrolysis of sorghum straw to obtain xylose solutions has a double consequence, the elimination of a waste and the production of a value-added product that increases the economy of the process [11].

The hydrolysis reactions in dilute-acid medium are very complex, mainly because substrate is in a solid phase and the catalyst in the liquid phase [12-14]. The acid hydrolysis of the hemicellulosic fraction of sorghum

stalk may also lead to a valuable solid residue mainly cellulose and lignin. Thus, the acid hydrolysis can be conceived as the first stage of an integrated strategy for sorghum stalk utilization [15].

In the course of dilute acid hydrolysis of agro-residues, parameters such as reaction temperature, reaction time, acid concentration and solid-to-liquid ratio play critical roles in optimum sugar recovery and minimum generation of inhibitors [16]. The establishment of these parameters is of fundamental importance to define optimal conditions of hydrolysis to ensure the success of the process, in view of concerns taken into account since the hydrolyzate are used as fermentable hydrolyzed medium [17].The choice of the optimal hydrolysis conditions is very important for maximum yield of sugars and minimal formation of toxic compounds. This should be a low-cost process to ensure the sustainability of this technology and successful agro-residual feedstock management [18-20]. In this context, designing of reactors or changes in their configuration is an important consideration for the maximum de-polymerization of hemicellulose using dilute acid hydrolysis [16, 21, 22].

The purpose of present work is to demonstrate dilute acid hydrolysis data on sorghum stalks. The work is divided into three distinctive phases: i. Investigates the effect of pretreatment on sugar yield; ii. Determine the effect of dilute acid hydrolysis on process parameters; iii. Determine acid saccharification efficiency of the pretreated solids and variation of monosaccharide compositions with respects to hydrolysis variables. The main objective of this work was to define the optimum condition to liberate maximum sugar from sorghum stalks residues which is converted to ethanol.

2. MATERIALS AND METHOD

2. 1. Raw Materials   Sorghum stalk collected from local farm was used as raw material. The stalks were cut into small size and dried at room temperature and then was milled and sieved (Damavand sieve Ind., Tehran, Iran) to achieve a particle size in the range of 20-80 mesh (0.18-1 mm) and stored in plastic bag at room temperature till use. The sorghum stalks residue mainly consisted of cellulose, hemicelluloses, lignin and ash. All chemicals (hydrochloric acid and sodium hydroxide) used for this work were purchased from Merck (Darmstadt, Germany). The constituent of original dry sorghum stalks used in this study presented in Table 1.

2. 2. Pretreatment   The objective of the pretreatment of biomass with different concentration of alkaline solutions and variable solid loading was to upgrade the acid hydrolysis with high sugar concentration. In fact pretreatment may enhance the quick penetration of acid into the texture of biomass. The sorghum stalks were soaked in 0.125, 0.25 and 0.5 M NaOH solutions at a solid loading of 3, 5 and 7% in 5000 mL Erlenmeyer flask. The flask was cotton plugged and consequently autoclaved at 121°C for 60 min. The pretreated sample was neutralized with acid solution and then hydrolyzed with desired acid concentration.

2. 3. Reaction Vessel for Dilute-Acid Hydrolysis
Hydrolysis experiments were carried out in a 5 L batch hydrolysis reactor. The basic reactor is a cylindrical Plexiglas tube with dimensions of 30 cm length and id of 18 cm (Figure 1). The reactor temperature was controlled by a thermocouple inserted into the reactor. The hydrolysis reaction was carried out at 35, 55, and 75°C. It was possible to open up the reactor for cleaning and filling purposes. On one end, a ball valve size of 2cm id was installed for discharging the hydrolyzate. The sample line and acid reservoir are bolted tightly to the reactor. The reactor was filled with 3, 5 and 7% of dried sorghum stalk and the required amount of acid (3, 5 and 7% of hydrochloric acid concentration). Mechanical mixing was provided to have uniform solution by means of suitable impellers. The impellers were made of stainless steel with a 1.5 cm length and a 1.2 cm width; for all experiments agitation is fixed at 300rpm. The average time required to reach the desired reaction temperature was 5 min and the reaction time was 10 h.

TABLE 1. Analysis of dry sorghum stalks

Composition of Sorghum Straw	Content (%)
Cellulose	47.58
Hemicellulose	24.66
Lignin	24.73
Ash	3.03

Column length = 30 cm,
Vessel ID = 18 cm
Width of baffle = 1.2 cm

Impeller W = 1.2 cm
Impeller L = 1.5 cm

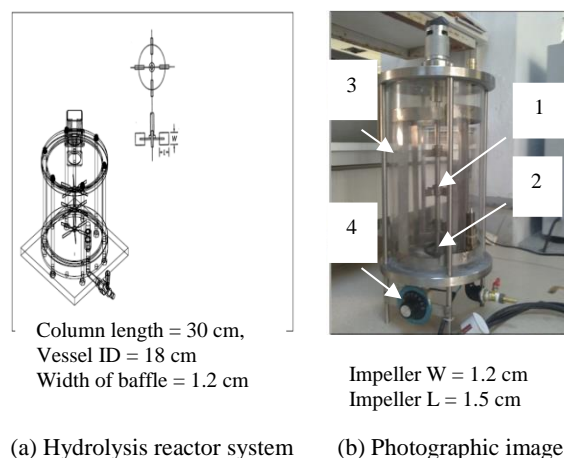(a) Hydrolysis reactor system   (b) Photographic image

Figure 1. Schematic diagram of the reaction vessel:1. Mixing impellers, 2. Heating element, 3. Baffles, 4. Temperature controller

2. 4. Analytical Methods

2. 4. 1. Chemical Structure Analysis using FTIR
Fourier transform infrared (FTIR) spectra are frequently used to investigate the structure of constitutes and chemical changes in lignocellulosic biomass. Solid samples were provided to identify the functional groups and structural properties of the sorghum stalk, before and after pretreatment by sodium hydroxide. The samples were analyzed by FTIR spectrometer (8400s, Nakagyo-ku, Kyoto, Japan).

2. 4. 2. Morphological Structure Analysis Using Scanning Electron Microscopy (SEM)
Scanning electron microscopy (SEM) was used to differentiate changes on the surface properties and microstructure of sorghum stalk before and after pretreatment and also after acid hydrolysis. A KYKY EM3200 SEM with an SN: 0386 absorbed-electrondetector (Zhongguancun, Haidian District, Beijing, China) was used to examine the microstructure of sorghum biomass before and after treatment in magnification range of 25x to 5Kx.

2. 5. 3. Sugar Analysis By DNS Method
In every 2 h time intervals, the sample was withdrawn for sugar analysis by opening a ball valve to allow the reactor contents to expand into a serum sampling bottle. In order to stop the reaction, the defined volume of the sample was immediately naturalized with a sodium hydroxide solution (pH value of 7). Then, the sample was centrifuged at 13000 rpm for 6 min. The total liberated reducing sugar in the hydrolyzate was analyzed by colormetric method using a reducing chemical reagent 3,5-dinitrosalicylic acid (DNS reagent) at wavelength of 540 nm, UV-VIS spectrophotometer (Jenway 6315, Keison product, Chelmsford, England) [17].

3. RESULTS AND DISCUSSION

3. 1. Sorghum Stalk with and without Pretreatment
The sorghum stalks residues were mainly consisted of cellulose, hemicelluloses, lignin and ash with composition of 47.58, 24.66, 24.73 and 3.03 %, respectively. During hydrolysis of pretreated material in every case the reducing sugar rapidly started to rise and then the rate was gradually decreased; that was due to availability of solid substrate. The reducing sugar concentrations of acid hydrolysis of sorghum stalk before and after pretreatment with 0.125, 0.25 and 0.5 M sodium hydroxide are shown in Figure 2.

There was a remarkable increase in reducing sugar concentration after the pretreatments. The concentrations of reducing sugars in the pretreated samples in compare to untreated samples increased by 50%. Based on reducing sugar concentration results the

sorghum stalk pretreated with 0.5M sodium hydroxide delivered maximum amount of liberated sugar under 121 °C pretreated materials. The hydrolysis reaction was found to be faster with the treated fiber. After the NaOH treatment, hemicellulose fraction of sorghum stalk would possibly solubilize. Furthermore, the cellulose fraction swelled and transformed from its crystalline form to the more reactive amorphous form [23]. In addition, it was also understood that lignin might be removed after NaOH treatment leaving carbohydrate fraction reactive towards the acid action [24]. Umikalsom and his coworkers [25] proved that an increase of reactive cellulose (ready to be involved in acid hydrolysis) and the reducing of lignin content were not only caused by the pretreatment of NaOH solution itself, but also by heat treatment. Within this chemical treatment of empty fruit bunch fiber, the autoclaving was believed to modify the physical structure of lignin while the NaOH solution acted on an effective intra crystalline swelling agent [21].

3. 2. Hydrochloric Acid Hydrolysis
Acid hydrolysis of pretreated sorghum stalk residues was carried out in several sets of experiments. Batch experiments were conducted using HCl as the reaction catalyst. For maximum monomeric sugar production, three parameters were considered, such as solid percentage, acid concentration and reaction temperature with respect to reaction time. Each parameter was evaluated to determine the optimum reaction condition for the maximum liberated sugars. Hydrolyzates were obtained using HCl at 35, 55 and 75°C. At the elevated temperature, there is a possibility of decomposition of xylose and glucose to furfural and hydroxyl methyl furfural. However, the effect of temperature in kinetic studies of acid hydrolysis has a positive impact [26].

3. 2. 1. The Effect of Temperature on Sugar Concentration
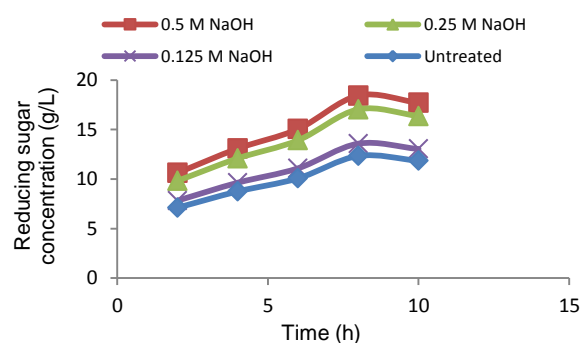The effect of temperature on acid hydrolysis is illustrated in Figure 3.

Figure 2. Reducing sugar concentration of untreated and pretreated sorghum stalks
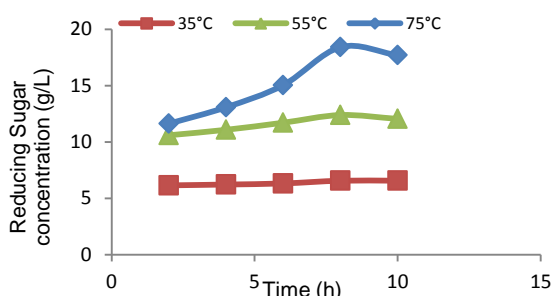
Figure 3. Effect of temperature on total reducing sugar at 7% HCl and 5% Solid

A temperature range of 35 to 75°C was studied. The sugar concentration at low temperatures was low. At a high temperature of 75°C, the concentration of sugar has easily reached to about 20 g/L. The high temperature increases the rates of hemicellulose sugars decomposition thus causes the formation of toxic compounds such as furfural and 5-hydroxymethyl-furfural (HMF). These compounds inhibit bacteria and yeast cells and the subsequent fermentation stage, causing a lower ethanol production rate [27, 28]. In addition, these compounds lead to reduction of fermentable sugars [27]. Harsh conditions used in treatment create a variety of toxic compounds that inhibit the fermentation performance. Inhibitors have been previously categorized by Olsson and Hahn-Hagerdal [29]. Specifically, furan derivatives including furfural and HMFare resulted from pentose and hexose degradation, respectively [30].

At low temperature, the rate of sugar release was slower than other temperatures; however sugar preservation was sustained for a longer period of time due to a low level of sugar decomposition which is simultaneously occurred. The rate of reaction is found to further increase when the temperature has risen to 55°C. After 8 h, the yield of sugar was maximized, about 10.39 g/L.

As is expected the sugar generation at 75°C had the highest reaction rate peak at 18.5 g/L. The reaction is more aggressive as reaching its optimum output; however it begins to decompose rapidly resulting at a low yield of 17.7g/L.

3. 2. 2. The Effect of Acid Concentration on Total Sugar Yield   The acid concentration is considered one of the most important factors regarding the release of sugars. High concentrations of acid may decompose the hemicellulose structure, producing inhibitors and also causing serious equipment corrosion.

Therefore, an appropriate acid concentration is essential for acid hydrolysis of lignocellulose at industrial scale [16]. As acid acts as a catalyst, it is evidently observed in Figure 4 that increasing acid

concentration will dramatically increase the reaction rate at a high temperature of 75 °C.

At 3% (w/w) hydrochloric acid concentration the rate of sugar production is slightly low, and over the course of the reaction only gradually increases. As the acid concentration started to rise the reactions rates began to increase rapidly. A noticeable shift in the sugar production rate is evident when the acid concentration is increased from 3 to 5% (w/w). The reaction takes place at a moderate rate at first increasing to its maximum concentration of 12.35 g/L at a reaction time of 8h.

At 75°C and 7% (w/w) dilute acid concentration, maximum yield was obtained. At retention time of 8h sugar concentration of 18.5 g/L was achieved. As the reaction continues a high rate of sugar decomposition resulted in a diminished final yield of sugars by the of the reaction period with only 17.7 g sugar/L remained.

From Figure 4, it can be concluded that the acid concentration has an important relationship with the rate of reaction for both sugar production and decomposition. At high temperature, longer reaction time may cause deformation of sugars to furfural and hydroxyl methyl furfural. One has to conclude that at high temperatures and in presence of acid catalyst, the undesired products are originated from pentose and hexose decomposition [28].

3. 2. 3. The Effect of Solid Percentage on Total Sugar Yield   Figure 5 shows the percentage of solid in acid hydrolysis. Three different percentages of solid (3, 5 and 7%) were studied. These conditions coincide with the other researchers' explanation that to a certain percentage of solid concentration of liberated sugar gradually increasing [31]. The lowest percentage of solid resulted in minimum sugar concentration. The concentration of liberated sugar with 7% HCl at 75°C for 3, 5 and 7% solid were 11.2, 18.5 and 21.7 g/L, respectively. As the solid percentage starts to raise the reactions rates begin to increase rapidly. A noticeable shift in sugar production rate is evident when the solid percentage is increased from 3 to 5%.
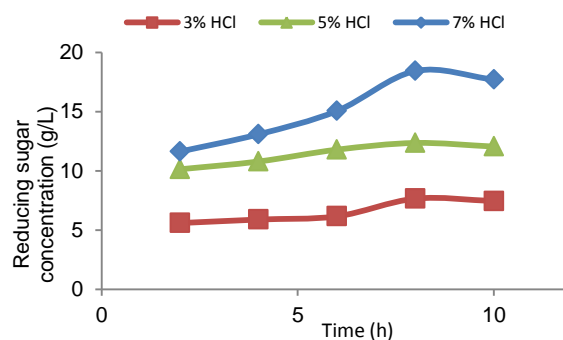

Figure 4. Total reducing sugar with respect to acid concentration using 5 % solid at 75 °C
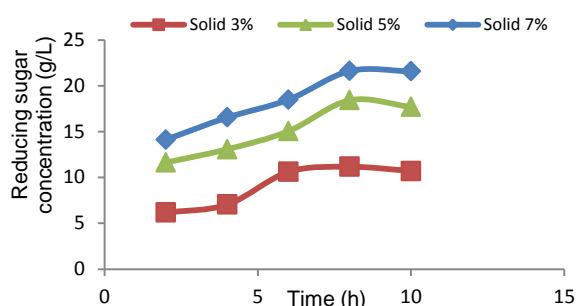
Figure 5. Total reducing sugar with respect to solid percentage at 7 % HCl and 75 °C

Further increases in reaction rate occurred as the solid percentage is increased to a level of 7%. A 5L batch continuous stirred tank reactor (CSTR) was employed for the experimental runs. The CSTR has not been of significant interest for the hydrolysis of lignocellulosic materials, possibly due to problems associated with mixing of very high solid content material, the sealing of the stirrer in a high-pressure reactor, and the high energy demand for mixing [16]. The maximum yield in the batch reactor is only about 40 % at 210 °C, the heart of the problem in dilute acid hydrolysis. In theoretical bases, application of high temperature, although it would increase the yield, it is simply not feasible because of operational difficulties may be originated from the rapid reaction rate [32]. On the other hand, beyond the optimum reaction time, the yield of reducing sugar concentration decreased gradually at high temperature for a long period of time and decomposition started to take place.

3. 3. Optimization of Reducing Sugar Production

The main purpose of present research was to optimize the reaction conditions for production of reducing fermentable sugar from sorghum stalk. The obtained hydrolyzates of sorghum stalk are used as carbon source in ethanol fermentation process. The effect of diluted acid hydrolysis on process parameters, the optimal reaction conditions were determined. Under the optimal conditions with 5% solid, maximum reducing sugar concentration of 20 g/L was obtained. The results indicate that the ideal hydrolysis condition for reducing sugar with 5% sorghum stalk and in a 7% hydrochloric acid solution was 75 °C for 8 h. Based on overall solid percentage, the process yield for the reducing sugar about 40%. Diluted acid hydrolyzates were fermented to ethanol by *Saccharomyces cerevisiae*. Highest ethanol concentration, 10 g/L was obtained. Lu and Mosier [33] hydrolyzed the corn stover, and the optimized yield of reducing sugar was 96% of theoretical. Canettieri et al. [34] hydrolyzed the forest residues; the highest reducing sugar yield was 87.6%, which was attained after 70 min

at 160 °C. Bustos et al. [35] hydrolyzed the sugar cane bagasse with diluted hydrochloric acid and obtained high sugar concentration. The optimal conditions selected were 128°C, 2 % HCl, and 51.1 min. Under these conditions, 22.6 g of sugar/L was obtained. Therefore, reducing sugar yield using sorghum stalk as raw material was slightly lower than that of corn stover and forest residues. The reasonable explanation might be related to sorghum stalk which has high 'hard-to-hydrolyze' fraction. However, as kind of waste biomass resources, sorghum stalk has low raw material cost, and has remarkable economic value. Ban et al. [36] hydrolyzed the sweet sorghum residue with phosphoric acid and fermented by *Saccharomyces cerevisiae*. Under optimum reaction conditions, a 30.24% yield of reducing sugar was obtained. The maximum obtained ethanol concentration was 14.5 g/L. Gyalai-Korpos et al. [37] hydrolyzed the sweet sorghum using enzymatic hydrolysis. At optimum conditions, the maximum reducing sugar was 78.9% (g/g dry substrate).

3. 4. FTIR Analysis

Supplemental Figures 6 (a) and 6 (b) show the FTIR spectra of untreated and pretreated sorghum stalk. As illustrated in these spectra; there were no new peaks in the spectra of unpretreated and pretreated sorghum stalk, but there were some differences in parts of peak transmittance. Therefore, there was no formation of new functional groups within the stalk in pretreatment process. Cellulose-related peaks in the FTIR spectra were 894.91, 1373.22, 2916.17 and 3332.76 cm⁻¹ [38-41]. The absorbance at about 3332.76 cm⁻¹, which is related to (O-H) stretching bond of hydroxyl group (Figure6 (a)), was increased after pretreatment by sodium hydroxide (Figure6 (b)). Moreover, sodium hydroxide resulted in broadening at the stated wave length [42]. This indicated the weaker intra- and intermolecular hydrogen bonding and lower crystallinity and after pretreatment, this absorption reduced, which indicated that less hydroxyl and phenol existed compared to the control [42]. The peak at 2916 cm⁻¹ (attributed to (C-H) stretching in aliphatic moieties like methyl/methylene portions in cellulose) was disappeared after pretreatment. It is showed that these linkage was broken [40, 43-45]. The spectrum at 1373.22 cm⁻¹ is due to (C-H) deformation (symmetric) of cellulose [38, 39, 41]. After pretreatment, its intensity decreased. This decrease implies that cellulose was decrystallized because of the applied pretreatment. The absorbance at 1249.79 cm⁻¹, which is related to (C-O) stretch of ether bonds (ar-C-O-C-al) from alkyl ester of the acetyl group in hemicelluloses, was disappeared after pretreatment [40, 43-45]. The spectrum at 1650.95 cm⁻¹, which are the adsorption peak of carbonyl groups (C=O) stretching and aromatic ring vibrations, was almost disappeared, proves that the hemicelluloses are almost removed from the natural fiber and much of lignin was

weakened.The spectrum at 1512.09 cm^{-1}, attributed to the (C=C) of lignin (the stretching of the phenyl ring), was observed for untreated biomass and was strong in intensity for sorghum stalk. This spectrum remained after pretreatment.The other spectra<600 cm^{-1} were attributed to the presence of metallic or inorganic content from the ash. This results from inorganic constituents that separate from the lignocellulose structure and accumulate during particle size reduction by milling [43].

Lignin characteristic can be followed by the peak at 1319.22 cm^{-1} ((C-O) of guaiacyl ring) (Figure6 (b)). The intensity at this wavelength for pretreated materials was significantly lower than that of the untreated sorghum stalk, indicating the delignification effect of the corresponding pretreatment[46]. Figure 6 (b) shows that the absorption at 1635.52 cm^{-1} represents the bending mode stretching of the absorbed water and stretching of (C=O) in lignin [47].
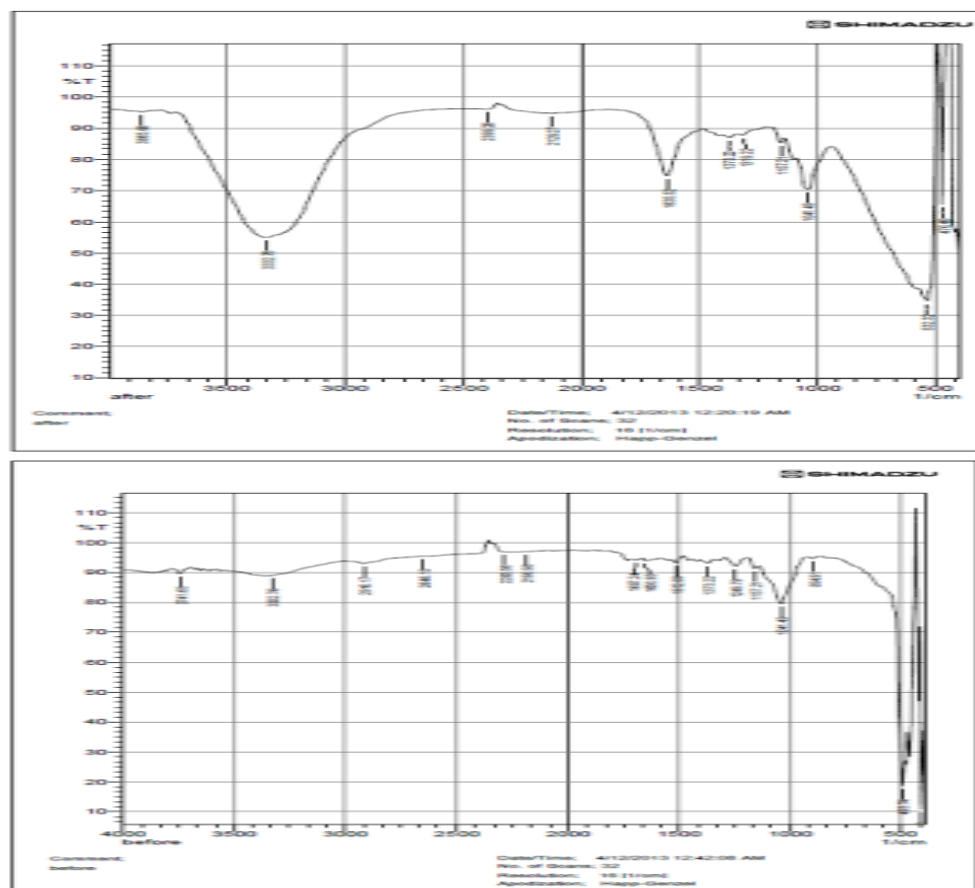

Figure 6. FTIR spectra (a) untreated sorghum stalk (b) FTIR spectra of pretreated sorghum stalk

3. 5. SEM Photo Analysis　　　SEM was used to study the morphological features and surface characteristics of materials after the pretreatment and the hydrolyzed biomass compared with the untreated sorghum stalk. The hydrolysis and pretreatment resulted in significant physical changes (Figure7 (c-f)). As shown in Supplemental Figure7a, the surface of the untreated sample was glazed, and there were no damage in the sample. Untreated sample seems to have deposits on the surface. This surface layer can include waxes, hemicellulose, lignin, and other binding material. It was also observed some internal plant structures such as vascular bundles and holes in the cellulose wall used for ventilation and metabolism (Figure7 (b)).

The particle sizes of untreated samples were 37.5, 45 and 55 μm.The pretreatment resulted in significant physical changes (Figures 7 (c) and 7 (d)). In fact, sodium hydroxide disrupts the structure of the fibers. Furthermore, the structure of the lignocellulosic biomass was opened up and more sponge-like structures were observed after the pretreatment, which can provide high surface area for subsequent acid hydrolysis reactions. The structure of the sodium hydroxide pretreated sample was loosened; the sample surface was cracked and rough. The sodium hydroxide pretreatment had a significant effect on the surface of the sample. There was distinct change in the dilute acid treated sample as shown by the SEM monogram (see Figures 7 (e) and 7 (f)).
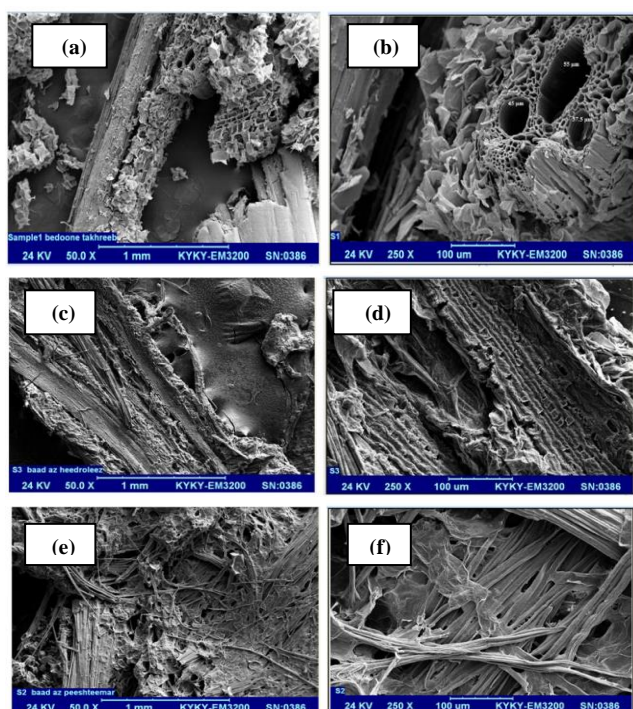
Figure 7. SEM images of untreated ("a" and "b"), NaOH pretreated ("c" and "d") and hydrochloric acid hydrolysis ("e" and "f") with magnification of50 and 250 x

The monogram shows an array of micro- holes in the sample. This increased the accessibility of the cellulose. The dissolution of the sorghum in hydrochloric acid hydrolysis seems to be completely disintegrated the fibers and made a uniform structure with less vacant area in the sorghum.

The analysis of SEM images showed that the internal and external structures of the sorghum were changed by the pretreatment of sodium hydroxide, thus increasing the cellulose accessibility by hydrochloric acid. According to the results of acid hydrolysis, the structure of sorghum and cellulose accessibility showed significant improvements on acid hydrolysis. It was observed that acid hydrolysis reduced and degraded cellulose, leaving a small final solid that might need further degradation.

4. CONCLUSION

From the hydrolysis of sorghum stalk residues, it was concluded that sorghum stalk residues showed great potential to be converted to a valuable product, which is monomeric sugar. A diluted acid hydrolysis process was employed in order to perform a moderate reaction condition at relatively low temperature and atmospheric pressure. For a reaction time of 8 hours, 5 % solid with 3, 5 and 7 percent of HCl, lignocellulose fibers conversion were 15.5, 25 and 37%, respectively. The sugar

concentrations in the acid hydrolysis of 5-7% solid within 8-10 h reaction time were 20 and 18.5 g/L, respectively. It was also concluded that an increase in sugar yield was proportional to both acid concentration and the temperature employed. In addition, with the prior treatment of sorghum stalk with 0.5M of NaOH, the yield on total reduced sugar increased. This may be attributed by the solubilization and swelling of hemicellulose and cellulose fraction and exposure of the sorghum stalk fiber to catalytic reagent. The work indicates that the use of sorghum stalk may be a feasible option as a feedstock for the production of sugars for bioethanol synthesis, due its low cost, considering its abundance and apparent ease of conversion.

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Hydrolysis of Sorghum (Broomcorn) in Diluted Hydrochloric Acid

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چکیده

تبدیل مواد لیگنوسلولزی به عنوان منبع تجدید پذیر از لحاظ اقتصادی مقرون به صرفه بوده و تاثیر زیست محیطی قابل توجهی دارد. برای استحصال قندهای قابل تخمیر فرایند هیدرولیز اسید رقیق تحت شرایط بهینه بکار گرفته شد. ساقه سورگوم جارویی، پیش تیمار قلیایی زیست توده و هیدرولیز اسید کلریک رقیق مورد بررسی قرار گرفت. واکنش هیدرولیز در یک راکتور با حجم ۵ لیتر انجام شد. پارامترهای فرایند شامل دما راکتور (۷۵-۳۵ °C)، غلظت اسید (۷-۳٪) و میزان سوبسترای جامد خشک (۷-۳٪ وزنی) مورد بررسی قرار گرفت. نتایج نشان داد که شرایط بهینه واکنش عبارت است از: غلظت ۵٪ ساقه سورگوم جارویی، دمای ۷۵°C و تحت اسید هیدروکلریک ۷٪ . بیشترین میزان قند استحصال شده تحت شرایط بهینه مقدار ۳۹٪ (g/ g) ماده خشک) بود. تجزیه و تحلیل SEM و FTIR از پسماند سوبسترای جامد تخریب بافت زیست توده و حذف گروه های عاملی مرتبط به الیاف سلولز را تایید می نماید.

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