

Biomass hydrolysis into sugars via activated carbon-supported sulfonic acid

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Abstract: An activated carbon-supported sulfonic acid catalyst was synthesized and employed as a hydrolysis agent for hydrolysis of model and real biomasses including cellulose, starch, cellobiose, and switchgrass. Model biomasses including cellulose, starch, and cellobiose were hydrolyzed at 90 °C for 6 and 24 h while switchgrass was hydrolyzed at 75 °C and 90 °C for 6, 12, 18 and 24 h. For model biomasses, highest glucose was produced from cellobiose corresponding to 237.1 ± 0.86 mg g⁻¹ after 24 h, whereas switchgrass yielded a maximum glucose of 72.67 ± 1.03 mg g⁻¹ after 18 h at 90 °C. In addition, effects of physical (ultrasonication) and chemical (NaOH and H₂SO₄) treatments prior to hydrolysis of switchgrass were also studied. The data suggested that physical and chemical pretreatments did not significantly the hydrolysis efficacy of sulfonic acid catalysts. From the results obtained, it appears that sulfonic acid catalyst has the potential for direct hydrolysis of lignocellulosic biomass.

Keywords: activated carbon, sulfonic acid catalyst, hydrolysis, biomass, switchgrass

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1 Introduction

The world energy demand has significantly increased for the past few decades due to rapid increase of population and number of automobiles (Agbor et al., 2011). At the same time, continual use of fossil energy has resulted in environmental issues such as increased amounts of gas emissions (Kumar et al., 2009). In order to fulfill the need for energy in many different sectors while limiting the ill-effects on the environment, it is crucial to develop alternative pathways to produce sustainable and clean energy. Energy from lignocellulosic biomass can provide many benefits due to the abundant availability and low cost of feedstock (Lynd et al., 2002;

Huang and Fu, 2013). Typically, carbohydrates in biomass are used as a source for biofuel production such as bioethanol and biobutanol (Alvira et al., 2010). Therefore, processes to convert carbohydrates into alcohols have to be developed so that bioethanol from lignocellulosic biomass could be effectively commercialized in order for biomass to alcohol industry to compete with the petroleum industry.

In general, to convert biomass into alcohols, several unit operations need to be employed (Agbor et al., 2011; Kumar et al., 2009). The first operation includes pretreatment of biomass to prepare the biomass matrix for subsequent hydrolysis to synthesize sugars (Chiaramonti et al., 2012). The final step includes fermentation of sugars into alcohols or other chemicals depending on the market demand. Biomass pretreatment involves physical, chemical, or biological processes that help the celluloses and hemicellulases access cellulose and hemicellulose portions of biomass matrix, although of late, chemical pretreatments using acids, bases, ammonia, ozone, and

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others are being widely studied. Despite their efficacy, the overall pretreatment phase can cost at least 20% from the total production expenses (Chiaramonti et al., 2012; Brodeur et al., 2011; Yang and Wyman, 2008). In addition, chemical pretreatment agents such as acids and bases are corrosive and hence need special containers for storage and pretreatment (Kumar et al., 2009). Further, after the pretreatment the spent chemicals need to be treated, which may add additional steps and cost to the overall economics (Chiaramonti et al., 2012). Considering these issues with liquid pretreatments, it was recently proposed to use solid acids/bases for pretreatment (Peña et al., 2014; Ansanay et al., 2014; Tan and Lee, 2015).

After biomass pretreatment, another significantly expensive unit operation in biomass conversion is hydrolysis of biomass. Typically cellulolytic and hemicellulolytic enzymes are used to hydrolyze the biomass into sugars (Jørgensen et al., 2007; Keshwani and Cheng, 2009). Although the process is effective and allows for conversions over 90%, the high cost of enzymes makes biomass to alcohol processes very expensive (Chiaramonti et al., 2012; Jiang et al., 2012). In addition, the spent enzymes cannot be recycled easily. Hence researchers are looking at alternate options to hydrolyze lignocellulosic biomass (Guo et al., 2012; Zhou et al., 2011).

One approach to hydrolysis of biomass is to use solid acid catalysts (Tojo and Hirasawa, 2013; Li and Qian, 2011). Solid catalysts can be synthesized easily and recycled with no significant loss of activity (Peña et al., 2014; Guo and Fang, 2013; Hu et al., 2014; Wang et al., 2012). Recently, Hu et al. (2014) and Wang et al. (2012) have explored hydrolysis of pure cellulose and cellobiose into sugars. Wang et al. (2012) reported the use of silica catalyst under hydrothermal conditions at 160 °C for 12 h reaction to hydrolyze cellulose and observed 73.3% cellulose conversion corresponding with 50.1% glucose yield. Similarly, SUCRA-SO₃H was able to hydrolyze ionic liquid-pretreated cellulose for 24 h at

120 °C and observed glucose yield of 55%, while starch was observed to achieve higher glucose yield of 92% hydrolyzing and cellobiose conversion reached 100% with the same agent of SUCRA-SO₃H (Hu et al., 2014).

While many studies have been conducted on model biomass components, to our knowledge solid acid catalysts have not been investigated extensively for direct hydrolysis of biomass. Based on literature and our limited preliminary data, it was hypothesized that biomass could be directly hydrolyzed using solid acid catalysts. Hence, in this research the overall goal is to explore hydrolysis of biomass into sugars using solid sulfonic acid catalysts. Specifically the focus were on studying the efficacy of activated carbon-supported sulfonic acid catalyst for (1) direct hydrolysis of switchgrass into fermentable sugars and (2) hydrolysis of switchgrass pretreated with ultrasound, sodium hydroxide, and sulfuric acid.

2 Materials and methods

2.1 Feedstocks

Switchgrass, maize starch, cellulose, and cellobiose were used as feedstocks in this research. Switchgrass was harvested in July 2011 from NCSU field labs and field dried. The stock was ground to pass size of 2 -mm sieve and stored in the lab until further use. The switchgrass consisted of glucan (28.14%), xylan (13.47%), acid soluble lignin (ASL) (3.21%) and acid insoluble lignin (AIL) (22.35%). Maize starch (CAS 9005-25-8), Lab Grade A cellulose (CAS 9004-34-6), and D (+) cellobiose (CAS 528-50-7) were procured from ACROS Organics and Fisher Scientific, respectively.

2.2 Catalyst preparation

Catalyst used in this study was prepared by impregnating 60 g of activated carbon (size between 1-2 mm) with *p*-Toluene sulfonic acid solution. *p*-Toluene sulfonic acid solution was prepared by mixing 67 g of *p*-Toluene sulfonic acid with 100 ml of deionized water. The activated carbon was soaked in the acid solution for 48 h, separated by vacuum filtration, followed by drying

for 2 h at 105 °C and calcination (heated in an oven in air) for 2 h at 250 °C.

2.3 Catalyst characterization

To quantify the total acidic sites on the surface of the catalyst, Boehm titration method was employed. Typically, 0.5 g of catalyst was equilibrated with three base solutions of 0.05 M NaHCO₃, 0.05 M Na₂CO₃ and 0.05 M NaOH at 125 r/min for 24 h at room temperature as described by Evangelin et al. (2012). After separating the catalysts from the solutions, 10 mL of each solution was titrated with 0.05 M HCl using Methyl red as indicator. It was assumed that carboxylic, lactonic, and phenolic groups were neutralized by NaOH, while NaHCO₃ neutralized carboxylic groups, and Na₂CO₃ neutralized both carboxylic and lactones groups (Evangelin et al., 2012; Mukherjee et al., 2011).

2.4 Batch experiments

All experiments were performed in triplicates in batch reactors in which catalyst and biomass was mixed (1:1) with 50 mL water. The feedstocks were converted into sugars according to the conditions summarized in Table 1. In the first phase, hydrolysis experiments were performed using pure feedstocks such as cellulose, cellobiose, and starch to obtain baseline data. The feedstocks were hydrolyzed using activated carbon-supported sulfonic acid catalyst for 6 and 24 h at 90 °C.

Table 1 Pretreatment and hydrolysis conditions employed for converting biomass into sugars

Feedstock	Prior Pretreatment	Hydrolysis Reaction time, h	Temperature, °C
Cellobiose	No	6 and 24	90
Starch	No	6 and 24	90
Cellulose	No	6 and 24	90
Switchgrass	No	6, 12, 18, 24	75 and 90
Switchgrass	Ultrasound -100% Amplitude, 5 min	6 and 24	90
Swicthgrass	Ultrasound -100% Amplitude , 15 min	6 and 24	90
Swithgrass	Ultrasound -100% Amplitude , 25 min	6 and 24	90
Switchgrass	NaOH 2% (w/v) Autoclave 1h, 121 °C	6 and 24	90
Swithgrass	H ₂ SO ₄ 1% (w/v) Autoclave 1h, 121 °C	6 and 24	90

In the second phase, switchgrass was hydrolyzed directly using the catalyst. However to ensure uniform mixing of batch reactor contents, the catalyst particles were dispersed into switchgrass particles using an ultrasonication system for one min. Switchgrass was hydrolyzed at 75 °C and 90 °C for four reaction times of 6, 12, 18 and 24 h. After hydrolysis, catalyst was separated manually from the mixing slurry followed by the separation of wet samples via vacuum filtration. The pH of the liquid hydrolysates was measured and glucose contents were determined. In the third phase, switchgrass samples were pretreated prior to hydrolysis via ultrasonication (physical), NaOH (chemical), and H₂SO₄ (chemical) (Table 1).

Physical pretreatment was conducted using Hielscher UIP 1000 hd corresponding to ultrasonication for 5, 15, and 25 min at 100% amplitude. Ultrasonication was selected due to the effectiveness of this method to disrupt cell walls, alter surface morphology of biomass and promote mass transfer and lignocellulosic dissolution (Yunus et al., (2010); Guo et al., (2012) Bussemaker and Zhang (2013), Liyakathali et al. (2016).

Chemical pretreatments included pretreatment in an autoclave with 2% NaOH and 1% H₂SO₄ for one h at 121 °C as suggested by Wang et al. (2010), Zhou et al. (2012) and Shi et al. (2011). After each pretreatment the biomass was separated via vacuum filtration, washed and prepared for sulfonic acid catalytic hydrolysis.

2.5 Soluble sugar analysis

Monomeric soluble sugars in the liquid were analyzed using a 2950 YSI biochemistry analyzer capable of determining concentrations of soluble sugars such as glucose and xylose. Typically, one ml of each sample was prepared in an Eppendorf tube and exposed to the enzyme immobilized sensor to obtain concentrations of glucose and xylose in g/L.

2.6 Statistical analysis

All experiments were conducted in triplicates. Data were analyzed using Proc Glimmix with confidence

limits of 95% using SAS 9.3 (Cary, NC) to understand the effects of catalyst and pretreatment on glucose yield. Additionally, Sigma Plot and excel solver were used for plotting.

3 Results and discussions

3.1 Catalyst total acidity characterization

The surface acidity data for the catalyst obtained from Boehm Titration are presented in Table 2. Compared to raw activated carbon (total acidity = $0.1 \pm 0.03 \text{ mmol g}^{-1}$) the total acidity of sulfonic acid catalyst ($0.51 \pm 0.01 \text{ mmol g}^{-1}$) synthesized in this research was about 5 times higher, suggesting that treatment of the catalyst resulted in impregnation of sulfonic acid groups on the surface.

Table 2 Catalyst acidity function

Acidic function, mmol g^{-1}	AC-pTsOH
Carboxyl	0.375 ± 0.003
Lactone	0.05 ± 0.003
Phenolic	0.085 ± 0.005
Total surface acidity	0.51 ± 0.01

3.2 Hydrolysis of pure feedstocks

The data obtained from hydrolysis (90°C) of cellulose, maize starch, and cellobiose are presented in Figure 1. When hydrolysis was performed without the catalyst, glucose yields from starch and cellobiose were minimal. The average glucose yields from starch was 0 mg g^{-1} after 6 h and 0.04 mg g^{-1} after 24 h, while cellobiose yielded 0.99 mg g^{-1} after 6 h and 1.64 mg g^{-1} glucose after 24 h reaction time.

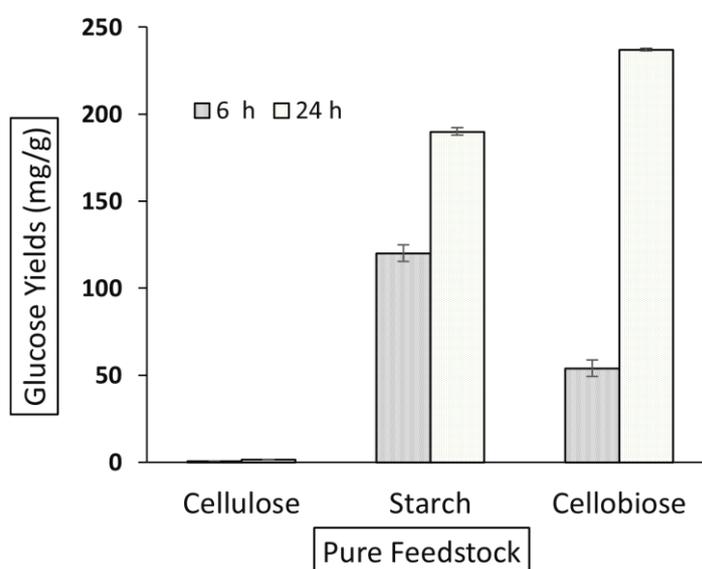


Figure 1 Hydrolysis of pure feedstocks using activated carbon-supported sulfonic acid catalyst.

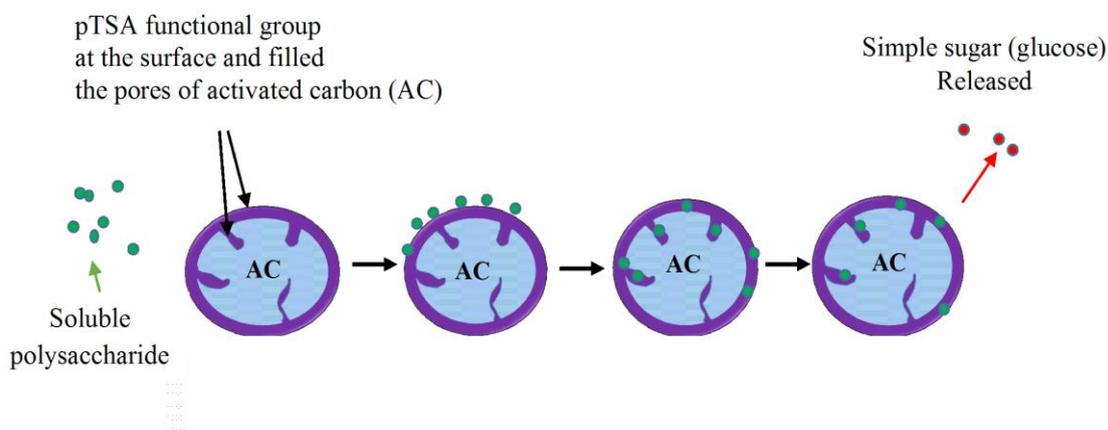
However, as expected, when catalyst was added to the system, glucose yield from starch and cellobiose increased gradually as hydrolyzing time increased. The rate of production of glucose from starch was initially faster up to 6 h and increased rather slowly thereafter to reach a maximum at 24 h. Most of the starches, including maize starch, are believed to consist of amylose and amylopectin (Green et al. (1975); Swinkles (1985); Naguleswaran et al. (2014)). Amylopectin, being a highly

branched structure, made the hydrogen bonding of this polymer prone to easy disassociation especially when higher temperature was employed. Meanwhile amylose, a tightly packed linear polymer, probably possessed strong intermolecular hydrogen bonding that was difficult to be accessed by water. It was theorized that during the first 6 h of hydrolyzing time, most of amylopectin dissolved into the water solution, resulting in a higher rate. However as the amount of dissolved starch available in

the slurry reduced, the rate of production of glucose was also slower than the first 6 h.

It is also observed that the rate of glucose produced (after 24 h) from cellobiose was higher compared to the starch. This is perhaps due to the simple structure of

cellobiose that consists only of two glucose molecules linked by a β , 1-4 glycosidic bonds. Therefore the catalyst was able to break the hydrogen bond relatively easily. In general, proposed steps in sulfonic solid acid hydrolysis are presented in Scheme. 1.



Scheme 1 Schematic mechanism of sulfonic solid acid hydrolysis.

We theorize that solubility of the feedstock is the key for successful hydrolysis. Furthermore, for hydrolysis to take place, soluble polysaccharide has to be in close contact with solid catalyst and followed by adsorption and diffusion into surface or internal pores of solid catalyst. At this stage, the hydrogen bonding of the dissolved polysaccharide is broken into simple sugars such as glucose as described by (Guo et al., 2012).

Therefore, in our research, the production of glucose from cellobiose ($237.1 \pm 0.86 \text{ mg g}^{-1}$ (conversion of $23.7\% \pm 0.08\%$)) was higher than that of starch ($190.07 \pm 2.02 \text{ mg g}^{-1}$ feedstock (conversion of $19\% \pm 0.2\%$)) after 24 h hydrolysis. These results are similar to those of Takagaki et al. (2008) who also hydrolyzed starch at 100°C for 15 h using HNbMoO_6 and Amberlyst-15 as solid acid catalysts. The authors reported a 21% glucose yield for HNbMoO_6 and that 3.4% glucose yield when Amberlyst-15 was employed (Takagaki et al., 2008).

In addition, rates of glucose formation from hydrolysis of cellobiose were found to be ranging between 50 ± 4.4 and $54.89 \pm 0.19 \mu\text{mol h}^{-1}$. The rates obtained in our research are comparable to carbon-based solid acid catalysts ($87 \mu\text{mol h}^{-1}$) reported by Kitano et al.

(2009). But our rates are higher than silica-supported nafion ($4.7 \mu\text{mol h}^{-1}$), Amberlyst 15 ($27.5 \mu\text{mol h}^{-1}$), Nafion NR-50 ($25.9 \mu\text{mol h}^{-1}$), niobic acid ($5.1 \mu\text{mol h}^{-1}$), and H-mordenite ($0.6 \mu\text{mol h}^{-1}$) (Kitano et al., 2009). Therefore, it appears that sulfonic solid acid catalyst prepared in our research is effective in converting cellobiose into glucose.

Interestingly, the catalyst seemed to be ineffective when cellulose was used as feedstock. A maximum glucose yield of $1.54 \pm 0.04 \text{ mg g}^{-1}$ was obtained at 90°C for 6 and 24 h. It appears that in addition to surface acidity of the catalyst (Zhou et al., 2011), solubility of the feedstock also plays a role in conversion. In our research the pH of the solution for all feedstocks tested were between 2.19 -2.39 ($4.07 - 6.45 \text{ mmol L}^{-1}$). However the solubility of cellobiose was the highest followed by starch and cellulose (Van Soest, 1994) corroborating that critical role of biomass solubility. Recently Hu et al. (2014) also observed similar trends with respect to cellulose hydrolysis via solid acid catalysts. The authors reported glucose yields of 4% and 3% from cellulose at 120°C (24 h) using $\text{SUCRA-SO}_3\text{H}$ and $\text{SUCRO-SO}_3\text{H}$ solid acid catalysts, respectively (Hu et al., 2014). As cellulose is

equipped with extensive hydrogen bonding and highly crystalline structure several authors suggested ionic liquid treatment to enhance hydrolysis activity of the catalyst (Guo and Fang, 2013; Wang et al., 2012; Zhu et al., 2006).

3.3 Ultrasonication-assisted direct hydrolysis of switchgrass

When switchgrass was hydrolyzed without the addition of catalyst at 75 °C and 90 °C at four hydrolyzing times of 6, 12, 18 and 24 h, glucose yields were between 5.7 mg g⁻¹ and 12.9 mg g⁻¹. However, in presence of catalyst, data presented in Figure 2 indicated that hydrolysis performed at 90 °C resulted in significantly higher glucose yields than 75 °C ($p < 0.05$).

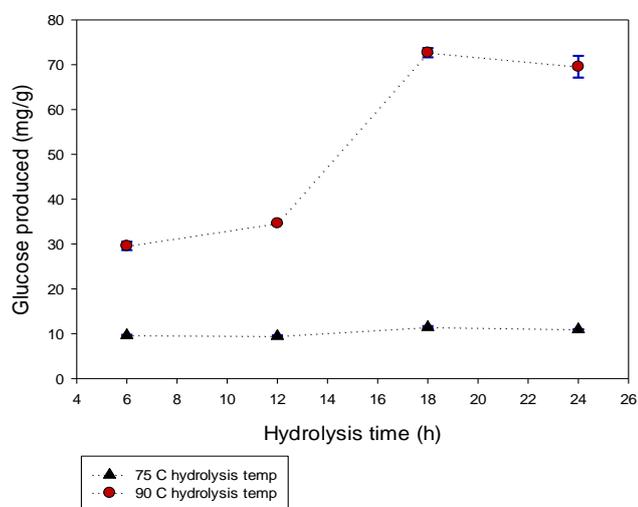


Figure 2 Sulfonic solid acid catalyst hydrolysis of switchgrass for 6 and 24 h at 75 °C and 90 °C.

The yields from four different hydrolyzing times at 75 °C were found not significantly different ($p > 0.05$). In addition, glucose yields at 90 °C after 18 and 24 h hydrolysis were also found not significantly different ($p > 0.05$), suggesting that glucose yields peak around 18 h. As expected, glucose yield increased with hydrolysis time and a maximum glucose yield of 72.67 ± 1.03 mg g⁻¹ (yield of $23.25\% \pm 0.33\%$) was achieved after 18 h of hydrolysis at 90 °C. Our results are similar to those of Li and Qian (2011), who studied the use of Amberlyst 15 Dry for hydrolysis of rice straw. In their research, a

maximum monosaccharides of 148.7 g kg⁻¹ rice straw yield was achieved at 150 °C after 3 h with the ratio of 10% solid content. In addition, 75 g kg⁻¹ of glucose was reported after 3 h of reaction and remained relatively stable up to 6 hours (Li and Qian, 2011). In a different study by Hu et al. (2014), SUCRA-SO₃H and SUCRO-SO₃H to hydrolyze carbohydrate from rice straw treated with ionic liquid (C₄mim. OAc) and reported glucose yields of 19.5% and 16.5% respectively. In a different study, liquid *p*-Toluene sulfonic acid (0.100 mol H⁺/L) was used to hydrolyze 0.1 g corn stover at 150 °C for 2.5 h. The authors, Amarasekara and Wiredu (2012), reported a maximum glucose yield of 35 μmol and 38 μmol at 160 °C. In our research we also obtained 53.49 ± 1.05 μmol (at 75 °C after 6 h) and a maximum of $403, 76 \pm 5.74$ μmol at 90 °C after 18 h. Extrapolating these results and comparing with ours, the authors, Amarasekara and Wiredu (2012) would have obtained 350–380 μmol of glucose, which appears similar to our results.

Similarly, Yamaguchi and Hara (2010) employed carbon-based solid acid catalyst bearing SO₃H, COOH and OH groups for hydrolyzing of Japanese cedar, bagasse and rice straw at 100 °C for 2 h using catalyst loadings of 2:2.5-3:4. The authors reported glucose yields of 14.3-42.5 mg g⁻¹, which is similar to the results obtained in our research. Therefore, activated carbon-supported *p*-Toluene sulfonic acid catalyst has the potential to directly convert lignocellulosic biomass into sugars.

3.4 Effect of pretreatment on hydrolysis of switchgrass

As shown in Table 3, pretreatment using ultrasonication appeared to have significant effect on glucose yield. Without the presence of the catalyst, the yield of glucose in the separated liquid after 5, 15, and 25-min ultrasonication pretreatment was limited to 1.38%-2.12%. However, after the same pretreatment times, liquid separated from switchgrass-catalyst mixture yielded glucose in the range of 7.32%-8.02%. The data suggested that catalyst was able to attack the cellulose

portion of the switchgrass matrix facilitate hydrolysis. As suggested by Harun et al. (2011) and others, localized intense energy pockets resulting from ultrasonication perhaps disrupted the structure of cell walls and exposed the cellulose to the catalyst. Similar observations were also reported by Shi et al. (2013), wherein the authors reported a significant increase in cellulose surface area as a result of ultrasonication. In addition, as presented from Table 3, when hydrolysis of ultrasonicated switchgrass was performed the glucose yields increased. When

switchgrass was hydrolyzed for 6 h, the glucose yields increased as pretreatment times increased. However, the data obtained after 24-h hydrolysis suggested that pretreatment times had no significant effect ($p > 0.05$) on glucose yields suggesting that the all sites on switchgrass matrix were occupied by the catalyst.

Table 3 Effect of ultrasonication on hydrolysis of switchgrass using solid acid catalyst

Conditions	Ultrasounds	Glucose yield, %	Glucose, mg g ⁻¹
Ultrasonication For 5 minutes	SG+Ult ^a	1.38 ± 0.002	4.30 ± 0.007
	SG+Cat+Ult ^b	7.32 ± 0.08	22.89 ± 0.25
	SG+Cat+Ult+6 h hydrolysis	12.95 ± 0.40	40.52 ± 1.27
	SG+Cat+Ult+24 h hydrolysis	16.81 ± 0.11	52.55 ± 0.36
Ultrasonication For 15 minutes	SG+Ult ^a	2.12 ± 0.01	6.63 ± 0.04
	SG+Cat+Ult ^b	7.65 ± 0.08	23.90 ± 0.25
	SG+Cat+Ult+6 h hydrolysis	15.11 ± 0.21	47.23 ± 0.65
	SG+Cat+Ult+24 h hydrolysis	16.91 ± 0.05	52.86 ± 0.16
Ultrasonication For 25 minutes	SG+Ult ^a	1.54 ± 0.08	4.80 ± 0.28
	SG+Cat+Ult ^b	8.02 ± 0.12	25.08 ± 0.38
	SG+Cat+Ult+6 h hydrolysis	16.76 ± 0.16	52.40 ± 0.49
	SG+Cat+Ult+24 h hydrolysis	16.80 ± 0.02	52.54 ± 0.06

^a Switchgrass was mixed with water under ultrasonication effect, ^b switchgrass was mixed with water contained catalyst under ultrasonication effect,

Combined physical treatment and solid acid catalyst hydrolysis of lignocellulosic biomass was recently studied by Jiang et al. (2012). The authors employed microwave irradiation and 1:1 catalyst: corncob biomass ratio and hydrolysis was performed for 20-120 h at 110 °C-140 °C. A maximum of 34.6% yield of glucose was observed after 60 h of hydrolysis at 130 °C and after 20 h hydrolysis at 140 °C (Jiang et al., 2012). While in our research, a maximum of 16.91% ± 0.05% of glucose was obtained after 15 minutes of ultrasonication followed by 24 h of catalytic hydrolysis. Therefore, our data supports that ultrasonication did impact the structure of switchgrass to improve the interaction between switchgrass and sulfonic solid acid catalyst.

Interestingly, chemical pretreatments of switchgrass did not have any effect on catalytic hydrolysis of switchgrass (Figure 3). It may be possible that after altering the surface of the switchgrass, chemical pretreatment may have formed an inhibitory barrier on the switchgrass surface preventing access to sulfonic acid catalyst. Hence, additional studies, especially those investigating the surface structural changes to the biomass surface are suggested. Further, it is also theorized that chemical pretreatments might impact the solubility of cellulose in the biomass matrix, which may in turn inhibit catalytic hydrolysis. Moreover, Mood et al. (2013) proposed a hybrid approach by combining multiple processes to enhance yield of glucose. Hence,

opportunities for integrating ionic liquids with solid acid catalysis may be explored.

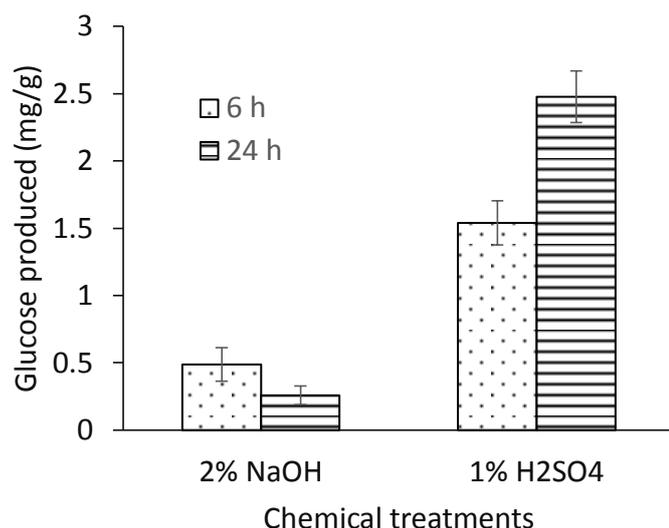


Figure 3 Glucose produced after 6 and 24 sulfonic acid hydrolysis from switchgrass treated with NaOH and H₂SO₄.

3.5 Practical implications

As the global energy requirements increase, lignocellulosic materials are expected to serve as feedstocks for synthesis of fuels and chemicals (Huang and Fu, 2013). Switchgrass is one such potential lignocellulosic resource that can grow with minimal inputs along with other environmental benefits (Wright and Turhollow, 2010). Based on our results, it may be possible to employ solid acid catalysts for converting switchgrass directly into glucose. As elucidated in their excellent reviews, glucose may also be transformed into several chemicals, including, Levulinic acid, Hydroxymethylfurfural and others which also serve as precursors for other chemicals via catalysis Wettstein et al., 2012; Bozell and Petersen, 2010). Current research on carbon-supported acid catalysts is expected to pave the way for more active and selective catalysts capable of hydrolyzing biomasses at lower temperature, thereby potentially eliminating expensive pretreatment processes. These catalysts combined with their multiple readabilities can not only facilitate efficient processing of biomass but also reduce the overall cost of production of glucose by

minimizing use of enzymes and make biomass to energy and chemicals pathways economical. In addition, as Wyman (2003) suggested, combining glucose production with chemical synthesis on a large scale will enhance profitability of the process.

4 Conclusions

An activated carbon-supported sulfonic solid acid catalyst was evaluated as a hydrolysis agent for conversion of cellulose, starch, cellobiose, and switchgrass into glucose. Experiments were conducted to investigate the effects of temperatures, reaction times, and pretreatments on sulfonic solid acid hydrolysis. Increased hydrolyzing time using sulfonic acid catalyst significantly affected formation of glucose from model biomasses including cellobiose and starch. Furthermore, reaction time and temperature were found to have significant effects for the production of glucose from Switchgrass. Meanwhile, among the three pretreatments agents used, ultrasonication with 100% amplitude as physical treatment was found to have improved the formation of glucose compared to 2% NaOH (w/v) and 1% H₂SO₄ (w/v). Therefore, it may be concluded that use of activated carbon-supported p-Toluene sulfonic acid catalyst can be potentially used to directly convert carbohydrate from lignocellulosic biomass into fermentable sugars.

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