Influence of AFEX™ pretreated corn stover and switchgrass blending on the compaction characteristics and sugar yields of the pellets

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ABSTRACT

The objective of this research was to investigate the impacts of Ammonia Fiber Expansion (AFEX™) pretreated corn stover and switchgrass blending ratio (25:75, 50:50 and 75:25 percent on dry weight), compressive pressure (31.6, 94.8, and 158.0 MPa), and screen size (2 and 4 mm) on pellet unit density, pellet hardness, specific energy consumption for pellets production, and the sugar yields. A single pelleting unit was employed in the study, and the untreated, AFEX™ pretreated, and AFEX™ pretreated blended samples were pelleted. The pellets produced from AFEX™ pretreated samples reached their maximum pellet unit densities at an applied pressure of 94.8 MPa. Pellet hardness was tested by applying the force to the pellets and recording the maximum force required to break. Results showed that the pellets produced from the small screen size sample at a higher applied pressure required more force to break. Besides, blend with higher proportion of AFEX™ pretreated corn stover produced harder pellets (711 N). Specific energy consumption for the pellets production varied from 11.4 to 57.9 kWh^t⁻¹, and due to low bulk density of switchgrass, blends with a higher proportion of switchgrass

consumed more energy for pellet production. Glucose yields of the AFEX™ pretreated samples were enhanced by 4 to 4.5 times and the xylose yields by 2 to 2.5 times compared to the untreated samples. Pelleting and biomass blending had no significant effects on sugar yields of the AFEX™ pretreated corn stover and switchgrass samples.

Keywords:

AFEX™ pretreatment; Pellet hardness; Enzymatic hydrolysis; Densification; Corn stover; Switchgrass

1. Introduction

The Energy Independence and Security Act of 2007 mandates the United States to produce 36 billion gallons of renewable biofuels annually by the year 2022 (Sissine, 2007). Considering the sustainable and environmental friendly characteristics, lignocellulosic biomass appears to be an alternative source to the fossil fuel usage. Greene and Mugica (2005) suggested the research focus towards demonstration and development of effective lignocellulosic biomass pretreatment, production of diverse bioproducts, and cost effective biofuels production from high yielding feedstocks. Preprocessing is a crucial phase in the biomass supply chain, which involves different operations to convert the harvested biomass appropriate for the end use in biorefineries. Conventional biorefinery adopts centralized processing approach, however, by shifting the preprocessing operations to the storage sites, the risks associated with handling diverse formats of biomass can be eliminated at the processing site (Hess *et al.*, 2007). Wright *et al* (2006) showed the improvement in transportation, handling, and merchandising potential of the biomass processed through distributed processing. A network of distributed processing facilities termed as ‘Regional Biomass Processing Depot’ (RBPD) involves different operations such as feedstock procurement, pretreatment, **densification, and delivery of single product to the biorefineries** (Eranki *et al.*, 2011). The authors showed that RBPDs produce similar net energy yield and reduce greenhouse gas emissions by 3.7 percent than the centralized conventional system.

Overcoming the biomass recalcitrant nature is one of the key challenges in biofuel production from lignocellulosic feedstocks (Brodeur *et al.*, 2011). Biomass pretreatment is a vital preprocessing operation in breaking the complex chemical structure, thus separating the cellulose and hemicellulose components from lignin matrix and making them available for enzymatic

hydrolysis. Developing an effective and economical pretreatment process is imperative in producing biofuels at a competitive price. Ammonia Fiber Expansion (AFEX™) is a promising physiochemical pretreatment process, which involves treating the biomass with liquid ammonia at a moderate temperature and pressure (Balan *et al.*, 2009). The process involves treating biomass with liquid ammonia under moderate pressure (100-400 psi) and temperature (70 to 200°C) in a stainless steel reactor for a short residence period of 5-30 min (Bals *et al.*, 2010). The selection of optimum parameters like pressure, temperature, and residence time depends on the recalcitrant nature of lignocellulosic biomass (Balan *et al.*, 2009). Release of rapid pressure after the residence period marks the end of pretreatment process. This rapid release of pressure results in breaking of complex chemical structure of biomass, thus exposing cellulose and hemicellulose fibers for enzymes to attack (Chundawat *et al.*, 2011; Kumar *et al.*, 2009). AFEX™ pretreated corn stover (Teymouri *et al.*, 2005), switchgrass (Alizadeh *et al.*, 2005), and rice straw (Sulbarán-de-Ferrer *et al.*, 2003) exhibited an increase in sugar yields when subjected to enzymatic hydrolysis.

One of the important physical limitations in handling, transporting, and storing lignocellulosic biomass is its low bulk density, (Eranksi *et al.*, 2011) which directly influences the production cost of biofuels. Densification involves application of mechanical and thermal energy to the bulky biomass to produce uniform densified products for efficient handling, transport, and storage. Mani *et al* (2002) elucidated the basic mechanisms involved in densification process. During the first stage, the biomass particles rearrange to form a closely packed mass. In the second stage, plastic and elastic deformation of particles occur with the increase in the applied pressure. Biomass undergo reduction in the volume with an increase in the applied pressure, till attaining its true density during the third stage. Lignin, one of the components of lignocellulosic

biomass becomes soft and acts as a natural binder when subjected to high temperature and pressure (van Dam *et al.*, 2004). The softened lignin acts as a glue in sticking the fibers together. Different densification methods like baling, **pelleting**, briquetting, and compaction have been tested on different feedstocks (Tumuluru *et al.*, 2011). However, **literature** on the impacts of pretreatment and densification on physical quality of the pellets (durability, pellet density, bulk density, hardness, etc.) and sugar yields are limited. Hoover *et al* (2014) studied the impacts of AFEX™ pretreatment and pelleting of corn stover on physical quality of pellets and sugar yields from enzymatic hydrolysis. Rijal *et al* (2014) investigated the impacts of AFEX™ pretreatment and **ComPAKco** densification method of corn stover, prairie cord grass, and switchgrass on the sugar yields from simultaneous saccharification and fermentation (SSF) and simultaneous hydrolysis and fermentation (SHF). Sundaram *et al* (2015) studied the effects of AFEX™ pretreatment on the compression characteristics of corn stover, prairie cord grass, and switchgrass. To reduce the overall biofuel production costs and to enhance the energy balance of biomass supply and conversion chain, Shi *et al* (2013) proposed that the pretreatment and densification of mixed biomass feedstocks could be an effective method. Considering the potential of mixed biomass pellets and AFEX™ pretreatment as a promising pretreatment technology, this research was intended to study the impacts of AFEX™ pretreatment, blending, and densification on the physical qualities of the pellets and the sugar yields from corn stover and switchgrass.

2. Materials and Methods

2.1 Feedstock preparation

The feedstocks corn stover and switchgrass obtained from the local farms in Brookings, South Dakota were milled using a hammer mill (Thomas Wiley laboratory mill, USA) attached with screen sizes of 2 and 4 mm. The milled materials were sealed in plastic bags and sent to the Biomass Conversion Research Laboratory (BCRL, Michigan State University, MI,) for AFEX™ pretreatment. The optimum conditions used for AFEX™ pretreatment are provided in table 1. The samples received after the pretreatment were sealed in plastic bags and stored in the refrigerator at 4°C until further use. Initial moisture content of the samples was determined using oven drying method ASABE standard S358.2 (ASABE Standards, 2006). Dry weight of untreated corn stover (UCS), untreated switchgrass (USG), AFEX™ pretreated corn stover (ACS), and AFEX™ pretreated switchgrass (ASG) were determined and the blends were prepared based on the dry weight of individual biomass. Three different blends were produced viz. B₁ (25% ACS and 75% ASG), B₂ (50% ACS and 50% ASG), B₃ (75% ACS and 25% ASG). Moisture content of the samples and the blends was adjusted to 15 percent on a wet basis, considering the requirement of less pressure at higher moisture content to produce highly compacted pellets (Sundaram *et al.*, 2015). Moisture content was adjusted by addition of calculated quantity of distilled water and the contents were mixed using a kitchen aid mixer (Kitchen aid professional plus 5, St. Joseph, MI). Moisture adjusted samples were stored at 4°C in refrigerator and were thawed to the room temperature before beginning the experiments. The chemical composition of untreated corn stover and switchgrass was determined using National Renewable Energy Laboratory – laboratory analytical procedure (Sluiter *et al.*, 2007). The retention of the components cellulose, hemicellulose, and lignin after pretreatment is the unique

feature of AFEX™ pretreatment. Hence, for the calculations of enzymatic yields, the compositions of untreated samples were used (Campbell *et al.*, 2013).

2.2 Bulk and particle density determination

Bulk density of untreated and AFEX™ pretreated samples was determined by measuring the mass of the sample occupying a known container volume. A hopper and stand apparatus (Seedburo equipment Co, Des Plaines, IL) was used to determine the bulk density of the samples. Samples were fed through the hopper and the cylindrical container with a volume of 0.5 l was placed underneath the hopper to collect the samples. Surplus samples collected were removed by passing a thin wire across the top of the cylindrical container. Mass of samples collected in the container was weighed and was divided by the volume of the container to determine the bulk density. Particle density of untreated and AFEX™ pretreated samples was measured using a multivolume gas pycnometer (Micromeritics multivolume pycnometer 1305, Norcross, GA). The measurement was based on the pressure difference between the volume of reference cell and the sample cell. Helium gas was used as a displacement medium and three replications were carried out for each sample.

2.3 Single pelleting unit

Pellets were produced by compressing the biomass in a single pelleting unit similar to the unit reported in different studies (Tabil L and Sokhansanj, 1996; Adapa *et al.*, 2002; Mani *et al.*, 2002; Sundaram *et al.*, 2015). The unit comprised of a piston and cylinder assembly with a base plate. The cylinder had an internal diameter of 6.35 mm and height of were 6.35 and 76.2 mm. A mass of 0.5 g to 0.7 g of sample was fed into the cylinder and the piston attached to the texture

analyzer (TA HD plus, Texture Technologies Corp, NY) cross head was allowed to compress the sample at a speed of 50 mm min^{-1} . The contents inside the cylinder were heated by the heating element wrapped around it. The cylinder was heated to a temperature of $100 \pm 2^\circ\text{C}$ to simulate the commercial pelleting operation (Mani *et al.*, 2004). Thermocouple attached to the cylinder was regulated by a controller (SDC 120KC-A, Brisk heat corporation, OH) to control the temperature. The diameter of base plate was same as the cylinder diameter and bottom of the cylinder was rested on base plate during compression. To avoid the spring back effect, after attaining the preset load piston was allowed to maintain at same preset load for 30 s (Tabil and Sokhansanj, 1996). Ejection of pellets produced was carried out by attaching the bottom plate above base plate and the piston was lowered. Pellets were produced under three different applied loads viz. 1000, 3000, and 5000 N with corresponding applied pressures of 31.6, 94.8, and 158.0 MPa respectively. Three replications of each sample were compressed.

2.4 Pellet unit density and hardness

Dimensions (height and diameter) of the pellets were measured using a digital vernier caliper (Digimatic, Mitutoyo Corp. Japan) and the mass of sample using digital weighing balance (Mettler PM 2500 Delta range, Columbus, OH). The ratio of mass of a pellet to its volume provided the unit density of a pellet. Compressive resistance or hardness test mimics the environment where pellets underneath are subject to stress by the weight of pellets placed over it during transportation and storage conditions. Hardness of pellets was tested by crushing the pellets using a cylindrical probe (TA-4, Texture Technologies Corp, NY) attached to the crosshead of texture analyzer. A single pellet was positioned in its natural position and a vertical force was applied at a speed of 50 mm min^{-1} to the pellet. The force applied vs deformation was

recorded by the exponent software (Stable Micro Systems Ltd, UK) and the maximum force recorded in the curve was taken as the pellet hardness.

2.5 Specific energy consumption

During the compression tests, force applied vs. displacement curve was recorded by exponent software (Stable Micro Systems Ltd, UK) and the energy spent for compression of biomass and ejection of pellets were calculated by integrating the area under the curve. The ratio of energy spent (for compression and ejection) and the mass of the sample were used to calculate the specific energy consumption and is given in kWh t^{-1} . Three replications of each sample compressed were used to calculate the specific energy consumption.

2.6 Enzymatic hydrolysis

Untreated, AFEX™ pretreated, untreated pelleted, AFEX™ pretreated pelleted, and blended samples were subjected to enzymatic hydrolysis following NREL protocol (Selig *et al.*, 2008). The enzymatic hydrolysis was carried out using 10 mL hungate glass tubes. Samples with the equivalent of 0.1 g of cellulose along with sodium citrate buffer (0.1 M, pH 4.8) was taken in the glass tubes. 100 μL of 2% sodium azide was added to inhibit the growth of organisms during the digestion. Enzyme loadings added were 15 FPU/g of glucan, 30 CBU/g of glucan, and 250 XU/g of glucan. All the enzymes were provided by Novozymes (Krogshoejvej, Denmark). The sample tubes were incubated at 50°C for 72 h in an incubated orbital shaker (MaxQ™ HP 420, Thermo scientific, MA) at an RPM of 150. After 72 h, the sample tubes were kept in boiling water for a period of 10 min to inactivate the enzymes. Supernatants from each tube were collected from hydrolyzed samples and were subjected to centrifugation at 13,000 $\times g$ for 15 min

in a centrifuge (Fisher scientific, Accuspin™ 400). The centrifuged samples were frozen and thawed twice to settle the impurities and the supernatant was taken in HPLC vials. The supernatants were injected into sugar analysis in an HPLC (Agilent Technologies, Santa Clara, CA; Bio-rad Aminex 87H column, Hercules, CA) to quantify the sugars present in the samples. A sample volume of 20µL was injected into the column at a flow rate of 0.6 ml/min at a 65°C column temperature. Sugar yields were calculated using Selig *et al* (2008) procedure by considering the chemical composition of the samples and the concentration of sugars obtained from HPLC analysis.

2.7. Statistical analysis

Least significant difference test was carried out using PROC GLM method in the SAS web editor (SAS 9.3, Cary, NC) to determine the significant effects of selected parameters on the pellet properties and the sugar yields. Level of confidence was set at 95%.

3. Results and discussion

3.1 Bulk and particle density

Bulk and particle densities of untreated, AFEX™ pretreated, and blended samples are reported in Table 2. Mani *et al* (2006) reported the bulk density of corn stover as 156 kg m⁻³ (1.6 mm screen size) and 131 kg m⁻³ (3.2 mm screen size). Similarly for the switchgrass, bulk densities were reported as 156 kg m⁻³ (1.6 mm screen size) and 115 kg m⁻³ (3.2 mm screen size). In this study, the bulk density of untreated stover (UCS) was 120.9 kg m⁻³ (2 mm screen size) and 107.3 kg m⁻³ (4 mm screen size). Untreated switchgrass bulk density was 115.5 kg m⁻³ (2 mm screen size) and 100.8 kg m⁻³ (4 mm screen size). Compared to the control samples,

AFEX™ pretreated samples exhibited higher bulk and particle densities. This could be due to the conversion of fibrous biomass into brittle material during AFEX™ pretreatment. Hoover *et al* (2014) noticed the brittle and friable nature of corn stover when subjected to AFEX™ pretreatment.

The mean bulk and particle densities of the sample ACS (2 mm screen size) was highest (237.8 kg m⁻³ and 1423.1 kg m⁻³ respectively) among all the samples taken and among the blended samples, blend with a high proportion of corn stover (B₃) at 2 mm and 4 mm screen size produced high bulk and particle density. AFEX™ pretreated corn stover sample had the higher bulk and particle densities than AFEX™ pretreated switchgrass and the presence of a higher proportion of corn stover could have increased the bulk and particle densities in the B₃ sample. Bulk densities of all the samples were statistically significant and the blending ratio and screen size had a significant effect ($p < 0.0001$). However, the mean particle densities of the blends B₁, B₂, B₃ for 2 mm screen size and blends B₂ and B₃ for 4 mm screen size were statistically similar. The factors blending ratio and screen size were not significant in deciding the particle densities of the blends. In all the conditions, bulk and particle densities of the samples increased with a decrease in the screen size.

3.2 Pellet unit density

Fig 1 shows the pellet unit density of 2 mm and 4 mm screen size samples compressed at different applied pressures. It can be inferred from the figure that, unit density of the pellets increased with an increase in the applied pressure for both screen size samples. The factors screen size, blending ratio, and applied pressure had significant effect on the pellet unit density

($p < 0.0001$), but their interactions were not significant. It was observed that the increase of pellet unit density was minor when the applied pressure was increased from 94.8 to 158.0 MPa. Stelte *et al* (2011) observed the minor increase in the pellet unit density of wheat straw, Norway spruce and European beech, when the pelleting pressure was increased between 250 and 600 MPa and major change in the pellet density was observed when the pressure was below 50 MPa. Similarly, Adapa *et al* (2009) reported the significant increase ($p < 0.05$) in the compact density of canola and oat straw when the pressure applied was increased from 31.6 to 94.7 MPa. When the pressure applied was increased above 94.7 MPa, there was no significant increase in the compact density as the compacts reached their corresponding particle densities. Similar fashion was observed in this study as the pellet unit densities approached their respective particle densities.

Particle density values reported were in the range of $900 - 1200 \text{ kg m}^{-3}$ for corn stover and $600 - 1000 \text{ kg m}^{-3}$ for switchgrass samples (Mani *et al.*, 2006). In this study, AFEX™ pretreated samples produced pellets with higher unit density than the untreated samples, representing the impact of AFEX™ pretreatment. During AFEX™ pretreatment the lignin – carbohydrate matrix structure is broken down and the components are free from the complex matrix, thus solubilizing and mobilizing the lignin to biomass surface (Dale, 1986; Bals *et al.*, 2010; Chundawat *et al.*, 2011). This increased availability of lignin could have contributed to better binding of AFEX™ pretreated samples compared to the untreated samples. Sundaram *et al* (2015) studied the impacts of AFEX™ pretreatment on the compression characteristics of corn stover, prairie cord grass, and switchgrass. The study showed the requirement of less pressure to produce highly compacted products after the feedstocks were subjected to AFEX™ pretreatment.

In this study, blend comprising higher proportion of corn stover (B₃, 2 mm screen size) at a maximum compressive pressure (158 MPa) produced pellets with maximum unit density (1416.25 kg m⁻³). Higher density of AFEX™ pellets can have benefits in transportation with fewer trucks or railcars necessary to transport the same weight of material (Hoover *et al.*, 2014).

3.3 Pellet hardness

Table 3 shows the hardness of pellets produced from untreated, AFEX™ pretreated, and AFEX™ pretreated blended samples at different applied pressures. Maximum pellet hardness (923 N) was recorded for AFEX™ pretreated corn stover pellets (2 mm screen size) produced at 158.0 MPa. AFEX™ pretreated corn stover pellets were strongest among the samples, and the sample with a high proportion of corn stover at 2 mm screen size (B₃) produced pellets with maximum hardness (711 N). Increased hardness of the corn stover pellets can be attributed to the higher lignin content present in the corn stover than the switchgrass samples. Lignin becomes soft and acts as a natural binder when subjected to high temperature and pressure (van Dam *et al.*, 2004). It was observed that the pellets produced from smaller screen size samples under maximum load can withstand maximum force before breaking. The hardness values of the pellets produced from 2 mm screen size particles were higher compared to the pellets produced from 4 mm screen size particles. This could be due to the increased surface area available for binding during the pelleting process. Tabil and Sokhansanj (1996b) observed that the screen size was not significant in determining the durability of the pellets, but smaller screen size particles produced more durable pellets. Jannasch *et al* (2001) reported the increase in pellet hardness of switchgrass when the particle size was decreased from 1/8 (3.2 mm) to 7/64 (2.8 mm) inch. Table 4 shows the main and interaction effects of the selected variables on pellet hardness. The

variables blending ratio, screen size, applied pressure and their interactions had a significant impact ($p < 0.001$) on pellet hardness. AFEXTM pretreatment impacts physical and chemical alterations to the structure of lignocellulosic biomass (Balan *et al.*, 2009; Dale, 1986). Lignin melting, depolymerization and depositing on the biomass surface (Dale, 1986; Chundawat *et al.*, 2011) are the significant alterations benefitting the biomass densification process. The increased availability of lignin in AFEXTM pretreated samples during the pelleting process could be the reason for increased pellet hardness compared to the untreated samples.

3.4 Specific energy consumption

Energy consumption comprises the energy required for biomass compression and ejection of pellets from the die. Energy spent for pellet production from different samples at different applied loads are shown in fig 2. The energy required for compression was relatively higher than the energy required for pellet ejection in all the conditions. The energy consumption ranged from 11.4 to 57.9 kWh t⁻¹, and it can be observed that the energy consumption increased with an increase in the applied pressure. Energy consumption for AFEXTM pretreated switchgrass pellets production was relatively higher than that of AFEXTM corn stover pellets, and the reason could be due to the low bulk density nature of switchgrass compared to the corn stover samples. Adapa *et al* (2002) reported the similar result when fractionated alfalfa grinds exhibited higher displacement values during the compression and the authors credited the reason to low bulk density of the feedstock. Among the blended samples, blend with equal proportion of AFEXTM corn stover and AFEXTM switchgrass (B₂) consumed higher energy (57.9 kWh t⁻¹). However, the magnitude of energy consumption for the pellets produced from 2 mm and 4 mm screen size samples was less. In other words, AFEXTM pretreatment had reduced the energy consumption

required for pellets production for large screen size samples. Statistical analysis showed the significant impact of selected variables and their interactions ($p < 0.0001$) on specific energy consumption. Table 4 shows the main and interaction effects of variables for specific energy consumption. In this study, the energy spent was relatively less when the pressure applied was increased above 94.8 MPa as the pellets approached their corresponding particle densities (Adapa *et al.*, 2009).

3.5 Enzymatic hydrolysis and the sugar yields

Table 5 shows the chemical composition of untreated corn stover and switchgrass samples. The glucose yields of 2 mm and 4 mm unpelleted AFEX™ pretreated corn stover (ACS) were 92.8% and 93.2% respectively. For unpelleted AFEX™ pretreated switchgrass (ASG), the glucose yields were 92.5% (2 mm) and 91.8% (4 mm). In the case of untreated corn stover (UCS), the glucose yields were 21.4% (2 mm) and 20.3 % (4 mm), whereas for switchgrass samples (USG) the yields were 18.8% (2 mm) and 19.5% (4 mm). It was observed that the glucose yields from AFEX™ pretreated samples were 4 to 4.5 times higher than that of untreated samples. Xylose yields of unpelleted AFEX™ pretreated corn stover were 45.8% (2 mm) and 46.9% (4 mm) and for unpelleted AFEX™ pretreated switchgrass the yields were 45.3% (2 mm) and 47.4% (4 mm). Untreated samples xylose yields were 15.5 % (2 mm) and 20.5% (4 mm) for corn stover and 13.1% (2 mm) and 19.4% (2 mm) for switchgrass samples. Increase in xylose yields of AFEX™ pretreated corn stover and switchgrass samples was 2 to 2.5 times higher than that of untreated samples. Increase in the glucose and xylose yields of AFEX™ pretreated samples compared to the untreated samples exhibited the influence of the pretreatment on the biomass. Lignocellulosic biomass have limited accessible surface area available for

enzyme interaction with cellulose components (Fan *et al.*, 1980; Hajny and Reese, 1969), due to the linkage of cellulose and hemicelluloses with lignin components acting as a physical barrier. AFEX™ pretreatment results in cellulose decrystallization, hemicellulose depolymerization, and cleaving of lignin-carbohydrate linkages (Balan *et al.*, 2009; Dale, 1986). These physicochemical alterations in the structure of biomass have resulted in enhanced sugar yields from AFEX™ pretreated corn stover and switchgrass samples.

Glucose and xylose yields of the pellets produced from AFEX™ pretreated and AFEX™ pretreated blend samples compressed under different pressures are shown in fig 3 (a and b). Glucose yields varied from 92.3 to 93.5% for AFEX™ pretreated corn stover pellets and from 91.8 to 92.5% for AFEX™ pretreated switchgrass pellets. Xylose yields of pelleted AFEX™ pretreated corn stover ranged from 46.8% to 48.9% and for AFEX™ pretreated switchgrass pellets the yields ranged from 45.3% to 49.4%. From fig 3, it can be observed that under different applied pressures, the yields of glucose and xylose from AFEX™ pretreated and AFEX™ pretreated blended pellets were not significant. In other words, pelleting pressure had a neutral effect on the glucose and xylose yields from the AFEX™ pretreated and AFEX™ pretreated blended pellets. Rijal et al (2012) also observed the densification of AFEX™ pretreated corn stover and switchgrass using ComPAKco technology had no significant effect on the sugar yields after 48 h of hydrolysis.

Reduction in biomass particle size increases the surface area to volume ratio, thus improving the enzymatic digestibility (Mansfield *et al.*, 1999). In this study, the screen size was not a significant factor in deciding the sugar yields from of AFEX™ pretreated corn stover and

switchgrass samples. Hoover et al (2014) noted the decrease in the sugar yields of AFEX pretreatedTM corn stover pellets when the grind size was increased from 4 mm to 6 mm. In this study, the screen sizes employed were 2 mm and 4 mm and no significant differences in the sugar yields were noted. This could be due to the increased surface area available for enzymes to interact with cellulose and hemicellulose components after the AFEXTM pretreatment. Glucose yields of the pellets produced from blended samples varied from 90.5% to 93.6% and the xylose yields varied from 45.3% to 49.5%. The statistical analysis showed that the sugar yields from the blended samples were statistically similar and blending of two different AFEXTM pretreated biomass had no significant effects. Shi *et al* (2013) also showed that the mixed biomass pellets produced from ionic liquid pretreated feedstocks had neutral effects on the sugar yield and it can be a viable and valuable resource considering the availability of biomass.

To summarize, pellets achieved their true densities at an applied pressure of 94.8 MPa and pelleting beyond this pressure did not produce denser pellets. Pelleting at different pressures had no significant effect on the sugar yields of AFEXTM pretreated and AFEXTM pretreated blended samples. Reducing the screen size from 4 mm to 2 mm had minor positive effect on the pellet physical qualities and no effects on the sugar yields. Use of the large screen size sample could decrease the energy required for raw material preparation for pretreatment and densification. Blending of two different lignocellulosic biomass had no significant effect on the sugar yields and the pellets produced from the AFEXTM pretreated mixed feedstocks could be a feasible resource considering the availability of biomass around the processing depots.

4. Conclusions

This study investigated the impacts of the blending of AFEX™ pretreated corn stover and switchgrass on the pellet compaction characteristics and sugar yields. Pellets were produced under different conditions using a single pelleting unit. Pellet unit density, pellet hardness, specific energy consumption for pellet production, and sugar yields were investigated. Following are the outcomes obtained from the study:

1. AFEX™ pretreatment increased the pellet unit density and pellet hardness of corn stover and switchgrass samples. Increase in pellet unit density was observed with increase in the applied load, and the AFEX™ pretreated samples achieved their maximum pellet unit density at 94.8 MPa applied pressure.
2. Pellets produced from the blend with a higher proportion of corn stover (B₃) (2 mm) produced strongest pellets with hardness of 711 N. Besides, the pellets produced from 2 mm screen size samples required more force to break than the 4 mm samples;
3. The variables blending ratio, screen size, and applied pressure had significant effect on energy consumption. The energy required for pellets production varied from 11.4 to 57.9 kWh t⁻¹, and the energy consumption increased with increase in the applied pressure. AFEX™ pretreated switchgrass required more energy for compaction because of its low bulk density compared to corn stover, and the blend with higher proportion of switchgrass consumed more energy;
4. Glucose and xylose yields of AFEX™ pretreated samples were 4 to 4.5 times and 2 to 2.5 times higher than that of the untreated samples. Biomass blending and pelleting had no significant effect on glucose and xylose yields of all the samples. These results indicate

that blending and pelleting the feedstocks can be a potential and viable option to minimize the logistical issues without affecting the sugar yields.

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Figure captions

- **Fig.1 Pellet unit density of the samples at different applied pressures**
- **Fig.2 Specific energy consumption of different samples at different applied pressures**
- **Fig.3 Sugar yields of pellets produced under different conditions (a) Glucose (b) xylose**

Pellet set 1 = 2 mm screen size samples compressed at 31.6 MPa; Pellet set 2 = 2 mm screen size samples compressed at 94.8 MPa; Pellet set 3 = 2 mm screen size samples compressed at 158.0 MPa; Pellet set 4 = 4 mm screen size samples compressed at 31.6 MPa; Pellet set 5 = 4 mm screen size samples compressed at 94.8 MPa; Pellet set 6 = 4 mm screen size samples compressed at 158.0 MPa.

(a) 2 mm

(b) 4 mm

Pellets produced from samples at different applied pressures

(a)

(b)

Table 1. Optimum AFEX™ pretreatment conditions employed for corn stover and switchgrass*

Feedstock	Ammonia loading (Ammonia: Dry biomass) (w/w)	Moisture content (db %)	Pretreatment soaking time (min)
Corn stover	1:1	60	15
Switchgrass	1:2	50	30

*Pretreatment was carried out at 100°C

Table 2. Bulk and particle density of different samples

Samples	Bulk density (kg m ⁻³)		Particle density (kg m ⁻³)	
	2 mm	4 mm	2 mm	4 mm
ASG	150.5 ± 3.5 ^f	116.3 ± 5.4 ⁱ	1368.6 ± 17.8 ^{bc}	1332.1 ± 11.3 ^d
B ₁	176.1 ± 2.8 ^d	135.9 ± 3.8 ^g	1369.1 ± 21.6 ^{bc}	1360.3 ± 25.0 ^{dc}
B ₂	202.5 ± 6.8 ^b	162.5 ± 6.3 ^e	1377.1 ± 19.0 ^{bc}	1374.0 ± 20.0 ^{bc}
B ₃	230.0 ± 8.1 ^a	190.3 ± 7.7 ^c	1385.4 ± 29.5 ^{bc}	1380.6 ± 20.5 ^{bc}
ACS	237.8 ± 6.9 ^a	197.3 ± 6.5 ^{bc}	1423.1 ± 11.2 ^a	1393.6 ± 13.8 ^{ab}
UCS	120.9 ± 4.7 ^h	107.6 ± 3.8 ^j	956.7 ± 7.8 ^e	923.5 ± 5.8 ^f
USG	115.5 ± 3.4 ⁱ	100.8 ± 2.7 ^k	905.2 ± 6.9 ^g	843.6 ± 9.7 ^h

Same letters in superscript within column for a given property are not significantly different ($p < 0.0001$)

Table 3. Pellet hardness of the samples compressed at different applied pressures

Feedstock	Pressure (MPa)	Pellet hardness (N)	
		2 mm	4 mm
ASG	31.6	132 ± 5.0	124 ± 16.9
	94.8	404 ± 79.6	361 ± 49.4
	158.0	564 ± 27.7	367 ± 63.3
B ₁	31.6	138 ± 7.3	135 ± 52.1
	94.8	394 ± 39.4	334 ± 24.1
	158.0	587 ± 22.9	556 ± 58.6
B ₂	31.6	120 ± 13.0	183 ± 33.7
	94.8	426 ± 17.2	355 ± 54.4
	158.0	626 ± 40.4	613 ± 32.8
B ₃	31.6	334 ± 51.6	173 ± 66.1
	94.8	668 ± 43.7	418 ± 51.6
	158.0	711 ± 94.1	633 ± 34.1
ACS	31.6	192 ± 81.8	410 ± 54.5
	94.8	771 ± 47.9	483 ± 89.8
	158.0	923 ± 72.2	805 ± 90.1
USG	31.6	107 ± 18.6	105 ± 35.7
	94.8	138 ± 27.5	129 ± 64.8
	158.0	272 ± 38.7	248 ± 28.4
UCS	31.6	128 ± 15.8	132 ± 34.8
	94.8	176 ± 40.0	186 ± 51.9
	158.0	307 ± 32.4	296 ± 19.9

Table 4. Main and interaction effects of variables on pellet hardness and specific energy consumption

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Pellet hardness					
Blend ratio	4	893904	223476	49	<.0001
Screen size	1	108736	108736	23	<.0001
Blending ratio* Screen size	4	64485	16121	3	0.0114
Applied pressure	2	3005969	1502984	331	<.0001
Blend ratio*Applied pressure	8	103422	12927	2	0.0094
Screen size*Applied pressure	2	104458	52229	11	<.0001
Blend ratio* Screen size*Applied pressure	8	162220	20277	4	0.0003
Specific energy consumption					
Blend ratio	4	395	99	63	<.0001
Screen size	1	2	2	2	0.2208
Blending ratio* Screen size	4	442	110	71	<.0001
Applied pressure	2	42448	21224	13607	<.0001
Blend ratio*Applied pressure	8	38	5	3	0.0033
Screen size*Applied pressure	2	186	93	60	<.0001
Blend ratio* Screen size*Applied pressure	8	160	20	13	<.0001

Table 5. Chemical composition of untreated corn stover and switchgrass

Feedstock	Glucan (%)	Xylan (%)	Arabinan (%)	Ash (%)	Lignin (%)
Corn stover	34.3	18.5	2.5	5.5	15.7
Switchgrass	32.2	14.8	2.3	3.7	13.3