The Canadian Society for Bioengineering
The Canadian society for engineering in agricultural, food, environmental, and biological systems.

CSBE | SCGAB

La Société Canadienne de Génie Agroalimentaire et de Bioingénierie
La société canadienne de génie agroalimentaire, de la bioingénierie et de l'environnement

Paper No. CSBE11-306

Radio Frequency-Alkaline Pretreatment of Lignocellulosic Barley Straw

Kingsley L. Iroba, Lope G. Tabil
Department of Chemical and Biological Engineering, University of Saskatchewan
57 Campus Drive, Saskatoon, SK CANADA S7N 5A9

Thomas Canam, and Tim Dumonceaux
Agriculture and Agric-Food Canada, 107 Science Place, Saskatoon, Saskatchewan S7N 0X2

Written for presentation at the
CSBE/SCGAB 2011 Annual Conference
Inn at the Forks, Winnipeg, Manitoba
10-13 July 2011

ABSTRACT The lignocellulosic nature of biomass presents resistance and 'recalcitrance' to the biological and chemical degradation of the lignocellulosic materials during enzymatic hydrolysis or saccharification, and the subsequent fermentation process. This leads to very low conversion rate, which makes the process uneconomically feasible. In this study, radio-frequency (RF)-based dielectric heating technique was used in the alkaline (NaOH) pretreatment of lignocellulosic biomass barley straw, so as to enhance its accessibility and digestibility by enzymatic reaction during hydrolysis. Due to the inherent and unique features of RF heating, samples can be pretreated under conditions which might not be conducive for microwave or the conventional heating methods. Two levels of sample particle size (1.6 and 0.8 mm), three levels of temperature (40, 50, and 60^{o}C), 1 h equilibration time, and two levels of NaOH concentration (0.5 and 1%) at 20 min residence time were used for the radio frequency pretreatment. The effect of the RF pretreatment was assessed through chemical composition analysis and densification of the pretreated and un-pretreated biomass samples. Statistical analysis showed that 1% NaOH concentration has significant effect on the average acid insoluble lignin, ash content, and the physical characteristics of the produced pellets.

Keywords: Radio Frequency technique, lignocellulosic barley straw, volumetric heat generation, alkaline pretreatment, and bio-ethanol.

INTRODUCTION The increase in the atmospheric CO_2 level has attracted worldwide attention. There is a general consensus in the scientific community that global climate change is caused by forced warming resulting from greenhouse gas (GHG) emissions, which is mainly from the combustion of fossil fuels (Fiona et al. 2007). These energy sources are not renewable because it

takes millions of years to be formed. There is fear of depletion of petroleum, coupled with increasing world population. As part of the strategies to mitigate the above effect; reduce the carbon footprint, and also enhance sustainability of energy supply, bioenergy and biofuels are espoused with lignocellulosic biomass as feedstock which is readily available, renewable, and carbon sink source of energy (Demirbas et al. 2009). Lignocellulosic biomass has an annual production of approximately 200 billion tonnes worldwide (Zhang 2008). Lignocellulosic biomass has long been recognized as a potential sustainable source of mixed sugars for fermentation to produce biofuels and other biomaterials. This will help to address climate change and create a healthier environment for today and tomorrow, avoid the competition between food and energy, create job opportunities, and generate revenue for the governments both at federal and provincial levels. Lignocellulosic biomass is a complex formation of cellulose, hemicellulose, and lignin. The lignin (which is normally deposited at maturity) acts as an external cross-linked aromatic polymer based on phenylpropanoid units binding hemicellulose and cellulose with cellulose positioned at the inner core of the structure. Hemicellulose has a random, branched, and amorphous structure with little strength. Cellulose is a polysaccharide with crystalline, amorphous, strong structure, and high degree of polymerization. Cellulose and hemicellulose have the potential for cellulosic bioethanol production. This lignocellulosic nature presents resistance and 'recalcitrance' to the biological and chemical degradation of the lignocellulosic materials during enzymatic hydrolysis and the subsequent fermentation process. This leads to very low conversion rate, which makes the process uneconomically feasible (Fan et al. 2006; Chandra et al. 2007; Mohammad and Karimi 2008). As such, initial pretreatment is required on the biomass prior to enzymatic hydrolysis.

Radio Frequency Technique Radio frequency (RF) has been successfully used in drying (Balakrishnan et al. 2004) and thermal therapy (Maurizio et al. 2004). Application of RF heating has been reported in other research fields such as food processing (blanching, tempering, pasteurization, sterilization) and medicine (Punidadas et al. 2003). In recent time, Izadifar et al. (2009) demonstrated that RF can be used for the extraction of podophyllotoxin from rhizomes of *P. peltatum*. In RF heating, there is a volumetric heat generation inside the product which is a result of the interaction between the RF waves and the molecules of the product, unlike conventional method where heat is being transferred from the heating medium to the product (conduction or convection). Microwave (MW) heating has the same principles and mechanisms of heating as RF heating. In RF and MW, heating is based on the product's ability to absorb electromagnetic radiation and convert it into heat (Ryynanen 1995). However, RF heating has the following advantages over the MW heating: uniform electric field strength inside the application chambers, therefore preventing thermal runaway, large penetration depth (10-30 meters), and higher energy efficiency. RF band has range of frequency between 3 kHz to 300 MHz, but typically 13.56-27.12 MHz and 40.68 MHz are used. The MW has 300 MHz to 300 GHz, typically 915 MHz, 2,450 MHz, 5.8 GHz, and 24.124 GHz are used. These bands of frequency range are selected and permitted for domestic, industrial, scientific, and medical applications so as to avoid interference with communication systems (Ryynanen 1995; Punidadas et al. 2003). RF heating can easily be scaled up unlike MW heating.

Densification In its natural form, most biomass are bulky, loose, and disperse, hence they are difficult to utilize as a fuel. Biomass as an energy source and as a feedstock for biorefinery does not present easy, economical, and efficient transportation, handling and storage characteristics due to large volume requirements (Tabil 1996; Mani et al. 2006a). To mitigate this condition is where densification gains extreme attention and importance. Biomass densification may be defined as the compaction or compression of biomass to eliminate inter- or intra particle empty spaces. Densification of untreated biomass feedstock is difficult and produces pellet with poor durability rating. Lignocellulosic biomass has a natural binder (lignin), which acts as an adhesive/glue that binds the biomass particles during densification process (Granada et al. 2002). To produce good quality pellets that could withstand the shear, impact, rotation, and tumbling during transportation

requires the released of this natural binder from the lignocellulosic matrix. Therefore, there is a need to fully or partially break (pretreatment) the lignocellulosic matrix in the biomass before densification so as to have access to lignin, and subsequently produce good durable pellets with high dimensional stability.

No study has been reported on the use of RF heating as a pretreatment method on lignocellulosic biomass barley straw. The possible applicability of RF as a pretreatment method on lignocellulosic biomass was confirmed in this research. The RF technique was applied using NaOH catalyst. The effect of the RF pretreatment was accessed through chemical composition analysis and densification of the pretreated and un-pretreated biomass samples.

METHODS AND PROCEDURES

Sample procurement and preparation Lignocellulosic barley straw was obtained in the month of October, 2009 from RAW Ag Ventures Limited, Maymont, Canada. The straw was ground using a laboratory grinder (Hammer mill; Serial no. GM13688; Glenmills Inc. 230 Brookdale, St. Maywood, NJ). Hammer mill screen sizes of 0.8 and 1.6 mm were used to grind the biomass straw. A dust collector (House of Tools, Model no. DC-202B, Saskatoon, SK) was connected to the outlet of the hammer mill to control dust during operation and to provide flow of the biomass straw in and out of the hammer mill. The initial moisture content of the straw was 8.8% (d.b.). The moisture content was measured based on ASABE standard method, ASAE S358.2 DEC1988 (R2008).

Particle and bulk density measurement The particle density of the samples was measured using the gas multi-pycnometer (QuantaChrome, Boynton Beach, FL 33426, model No. MVP-2) by calculating the displaced volume of nitrogen gas by a known mass of material. Three replicate tests were performed on each sample. The bulk density of the samples was determined by passing the material through a funnel which was placed above a standard 0.5 liter steel cup (SWA 951, Superior Scale Co. Ltd., Winnipeg, MB). Blockages in the funnel during biomass straw flow were cleared using a thin steel rod. After filling the cup, the excess was removed by passing a steel roller in a zig-zag manner over the top of the cup. The mass contained in the cup was then determined. Bulk density was calculated by dividing the mass of material within the cup by the volume of the cup. Three replicates were performed for each sample. The porosity of the ground samples was computed from the particle and bulk densities (table 1) using equation 1.

$$1-\frac{\rho_b}{\rho_p} \tag{1}$$

Where ρ_b is bulk density and ρ_p is particle density.

Radio Frequency Pretreatment The pretreatment was performed using RF machine (Strayfield 1.5 kW & 27.12 MHz laboratory dryer) with the following process and material variables: three levels of temperature (40, 50, and 60^{o}C), ratio 1:6 (35 g of biomass and 210 g of NaOH solution), biomass particle size of 0.8 and 1.6 mm, using 0.5 and 1% NaOH concentration, and 1 hour equilibration time. The biomass samples and the NaOH solution were properly mixed together in Lexan polycarbonate reactor, with 1 hour equilibration time at room temperature before subjecting the mixture to RF pretreatment. When the temperature gets to the preset point, 20 minutes retention time was given for the mixture to heat up. Each treatment combination was duplicated. Three fiber optic temperature sensors were connected to the reactor at three different locations to monitor the heat distribution (temperature profile not shown in this paper), see figure 1. The pretreated samples were dried to 10% moisture (w.b.) using thin layer dryer at 40^{o}C. To evaluate the efficiency of the pretreatment, chemical composition analysis and densification of the pretreated samples were carried out.

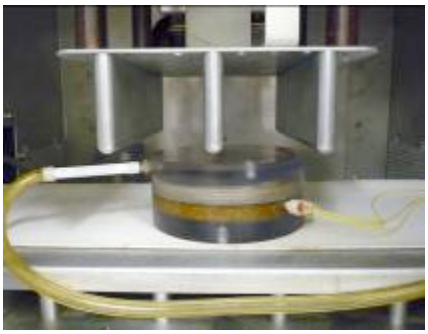

Figure 1. Lexan polycarbonates reactor containing the biomass NaOH mixture inserted between two electrodes of the RF machine.

Chemical composition analysis The National Renewable Energy Laboratory standard (Sluiter 2007) was used for the chemical composition analysis. Prior to this analysis, the biomass straw was bone dried at 105°C. The non-structural carbohydrates (nitrites, protein, ash, waxes, chlorophyll, etc.) were removed using acetone extraction process. The NREL standard uses a two-step acid (72% H_2SO_4) hydrolysis to fractionate the biomass into forms that are more easily quantified. The lignin fractionates into acid insoluble material and acid soluble material. The acid insoluble lignin (AIL) was calculated using equation 2 and the acid soluble lignin (ASL) was measured by UV-Vis spectroscopy and subsequently calculated using equation 3.

$$AIL = \frac{(dried\_retentate)}{(dried\_sample)} \times 100\% \quad (2)$$

$$\%ASL = \frac{UV_{abs} \times Volume_{filtrate} \times Dilution\_factor}{\varepsilon \times M_{sample} \times specpathlength} \times 100\% \quad (3)$$

Where UV_{abs} is the average UV-Vis absorbance for the sample at 240 nm, ε is feedstock absorptivity constant (110 $Lg^{-1}cm^{-1}$), M_{sample} is the dried sample mass (0.3 g), $Volume_{filtrate}$ is volume of filtrate (87 mL), and dilution_factor is the dilution factor of the sample (10). During the hydrolysis the polymeric carbohydrates (cellulose and hemicellulose) were hydrolyzed into monomeric forms (xylose, arabinose, glucose, galactose, and mannose), which are soluble in the hydrolysis liquid. These were measured using UPLC (Acquity 2004-2010, Waters Corporation, Milford, MA 01757, USA). The lignin piece and furfurals (5-hydroxyl-methyl furfural and furfural) were also measured using the UPLC. The chemical analysis was done using 300 ± 10 mg of each of the dried pretreated and untreated biomass straw.

Densification of pretreated and untreated samples The RF pretreated and untreated samples were densified using a single pelleting Instron machine. This unit includes a steel cylindrical die with a plunger/piston connected to the upper moving crosshead which provides the load necessary to compress the biomass samples. The die is surrounded with a heating element to provide the required heat for the process. About 0.5-0.7 g of the biomass feedstock was loaded into the die cylinder. The pre-set load (4 kN) and the required temperature (95±0.3°C) are adjusted to compress the charge material. Once the pre-set load is achieved, the plunger stops and held in position for 60 s retention time to avoid spring-back effect of biomass (Mani et al. 2006a), thereafter, the pellet is ejected. The Instron is typically set to lower the plunger (and compress the biomass) at a rate of 50 mm/min. The single-pelleter was connected to a computer which recorded the time and force-displacement data.

Durability test The durability or the hardness of the pellets was done after two weeks of storage, by dropping the pellets from a height of 1.85 m. The percentage durability was calculated by dividing the remaining piece by the original mass and multiplied by 100.

Tensile strength Diametral compression test was used to evaluate the tensile strength of the pellets (Tabil and Sokhansanj, 1996) using the single pelleting Instron machine. Pellets were cut diametrically using a scalpel into tablets with thickness of about 2.21 mm. Single tablet was placed on its edge on the lower padded plate and compressed with 1000 N load cell by the upper plunger at a crosshead speed of 1 mm/min until failure occurred. Fractures that caused the tablets to break or crack in two halves along the loading axis were accepted and other fracture types were discarded. Upon failure, the fracture force was recorded and the tensile strength of tablets was calculated using equation 4. Ten replicates were made for each sample.

$$\delta_x = \frac{2F}{\pi dl} \tag{4}$$

Where δ_x is tensile (horizontal) stress (Pa), F the Load at fracture (N), d the tablet diameter (6.67 mm), and l the tablet thickness (m).

Pellet density and dimensional stability The mass, length, and diameter of the pellets were measured immediately after pelleting and after two weeks of storage. These parameters were used to calculate the density.

Statistical analysis Experimental data were statistically analyzed using linear regression analysis performed at 95% confidence level using SPSS statistical software (version 14 for Windows, 2005 SPSS Inc).

RESULTS AND DISCUSSION Table 1 depicts the physical characteristics of the untreated biomass ground. It shows that as the particle size decreases the particle and bulk densities increases, while porosity increases with increase particle size.

Table 1: Physical characteristics of barley straw grind

Physical characteristics	Hammer mill screen size	
	0.8 mm	1.6 mm
Particle density (kg/m^3)	1361	1211
Bulk density (kg/m^3)	121	101
Porosity (%)	91	92

Chemical composition analysis Table 2 shows the chemical composition analysis of the RF pretreated and untreated samples. It shows that NaOH concentration is a major factor in the pretreatment. NaOH causes swelling and creates pores on the biomass, separating the structural linkages between lignin and the complex carbohydrates (cellulose and hemicellulose), leading to increased surface area, and thus enhances the reactivity of the matrix with any external added material such as enzyme. The higher the NaOH concentration, the lower the acid insoluble lignin. The reason for this solid loss is because, during the pretreatment process, the ester bonds between lignin and the complex carbohydrates are disrupted, some lignin are broken down, degraded, and perhaps solubilized, and subsequently washed away during the extraction process which was performed prior to the chemical composition analysis. This shows the reason why the untreated biomass has higher acid insoluble lignin. The implication of this is that the pretreated samples will have higher accessibility and digestibility during enzymatic reaction due to the already created pores. The higher the NaOH concentration the higher the ash content. 1% and 0.5% concentration increases the ash content by about 100 and 40%, respectively. This problem of increased ash content can be addressed by washing the pretreated samples. The statistical analysis performed shows that concentration has significant effect on the average acid insoluble lignin and ash content. There is no statistical difference observed among the average acid soluble lignin measured by UV-

Vis spectroscopy. This may be attributed to the low temperatures used in this experiment, as well as the capability of the UV-Vis spectroscopy.

Table 2 Chemical composition analysis of radio frequency pretreated barley straw grind

Tempt. (°C)	NaOH conc. (%)	Hammer mill screen size (mm)	AIL (%)	ASL (%)	Ash content (%)	% ash increase
40	1	1.6	17.48 (0.69)	1.86 (0.49)	12.18 (0.31)	104.28
50	1	1.6	17.01 (1.29)	1.47 (0.07)	13.99 (0.10)	134.71
60	1	1.6	16.18 (1.45)	1.48 (0.00)	12.20 (0.04)	104.61
40	0.5	1.6	18.02 (1.12)	1.43 (0.05)	8.49 (0.10)	42.45
50	0.5	1.6	17.97(1.97)	1.55 (0.03)	8.54 (0.04)	43.19
60	0.5	1.6	18.69 (0.25)	1.94 (0.59)	8.67 (0.12)	45.38
40	1	0.8	17.19 (0.12)	1.44 (0.00)	11.85 (0.37)	98.77
50	1	0.8	16.38 (0.98)	1.55 (0.11)	12.01 (0.29)	101.36
60	1	0.8	16.82 (0.78)	1.46 (0.01)	11.76 (0.12)	97.24
24	1	0.8	19.05 (3.28)	1.50 (0.01)	11.78 (0.11)	97.55
24	0.5	0.8	18.18 (0.64)	1.49 (0.04)	8.39 (0.46)	40.71
24	0	0.8	19.50 (0.37)	1.52(0.03)	5.96 (0.40)	0.00

Values in parentheses = standard deviation; n = 2, Tempt. = temperature, Conc. = concentration,

Table 3 depicts the average sum of 6 different lignin piece (4-hydroxybenzoic acid, vanillic acid, syringic acid, 4-hydroxybenzaldehyde, vanillin, syringaldehyde) and 2 furfurals (5-hydroxyl-methyl furfural (HMF), and furfural) analyzed using UPLC. It shows that the higher the NaOH concentration, the more pores are created on the lignin matrix, which makes it easy to access or solubilized the lignin component during the chemical composition analysis (two steps acid hydrolysis). The lignin in the raw sample is more difficult to solubilze during the chemical composition analysis, because the lignin matrix is tightly bonded. As such, it has the least solubilized lignin (329.12 ng/mg). Again, no statistical difference was observed on the HMF, which may be due to the low temperatures used in this experiment.

Table 3 Lignin and furfurals in radio frequency pretreated barley straw grind.

Tempt. (°C)	NaOH conc. (%)	Hammer mill screen size (mm)	HMF (ug/mg)	FUR (ug/mg)	Lignin (ng/mg)
40	1	1.6	2.49 (0.19)	30.37 (16.05)	464.79 (50.67)
50	1	1.6	2.25 (0.25)	36.65 (8.64)	525.38 (151.62)
60	1	1.6	2.68 (0.16)	43.09 (0.12)	550.60 (79.84)
40	0.5	1.6	2.53 (0.12)	35.24 (10.78)	379.50 (23.33)
50	0.5	1.6	1.88 (1.32)	27.20 (9.54)	385.83 (49.43)
60	0.5	1.6	2.71 (0.21)	40.70 (6.00)	415.99 (66.88)
40	1	0.8	2.43 (0.16)	37.49 (5.85)	545.15 (32.03)
50	1	0.8	2.51 (0.02)	34.86 (12.89)	574.01 (16.94)
60	1	0.8	2.64 (0.63)	33.40 (16.03)	507.82 (17.76)
24	1	0.8	2.43 (0.15)	35.50 (3.48)	587.18 (98.22)
24	0.5	0.8	2.69 (0.03)	30.41 (21.84)	398.67 (58.95)
24	0	0.8	2.70 (0.35)	43.17 (4.91)	329.12 (33.01)

Values in parentheses = standard deviation; n = 2, HMF = 5-hydroxyl-methyl furfural and FUR = furfural.

Table 4 indicates the average sum of the monomeric reduced simple sugars (xylose, arabinose, glucose, galactose, and mannose) measured using UPLC. The hemicellulose was calculated from

the sum of xylose, arabinose, galactose, and mannose. While cellulose was assigned to glucose. This is because the UPLC has no capacity to separate the glucose from cellulose and hemicellulose. The cellulose from the raw sample is higher because there was no initial degradation of the sugar unlike the pretreated samples.

Table 4 Cellulose and hemicellulose content of radio frequency pretreated barley straw grind

Tempt. (°C)	NaOH conc. (%)	Hammer mill screen size (mm)	Cellulose (%)	Hemicellulose (%)
40	1	1.6	11.57 (1.60)	13.61 (2.90)
50	1	1.6	14.77 (0.49)	11.24 (2.04)
60	1	1.6	12.00 (1.71)	13.04 (1.82)
40	0.5	1.6	12.08 (2.40)	11.56 (1.23)
50	0.5	1.6	10.63 (6.55)	10.45 (7.19)
60	0.5	1.6	12.02 (1.88)	14.07 (3.82)
40	1	0.8	13.94 (5.02)	17.47 (7.16)
50	1	0.8	12.74 (0.70)	13.86 (2.58)
60	1	0.8	13.94 (5.02)	15.50 (3.68)
24	1	0.8	10.17 (0.860	13.72 (1.01)
24	0.5	0.8	11.00 (1.35)	14.80 (0.50)
24	0	0.8	16.46 (3.23)	14.28 (1.65)

Values in parentheses = standard deviation; n = 2

Durability Table 5 shows the durability values of the pellets. Lignin plays a very vital role in the binding of biomass particles. RF pretreatment with 1% NaOH concentration produced pellets with higher durability. This is as a result of the pores which has been created on the lignin matrix during the RF pretreatment process, and subsequently made the binder (lignin) easily accessible during the densification process to produce durable pellets. Figure 2 shows the pellets produced using the single pelleting Instron machine. The high lignin value in Table 3 for samples pretreated with 1% NaOH confirmed that the lignin in pretreated samples were available for binding of particles. The statistical analysis performed indicated that concentration has significant effect on durability of the pellets.

Table 5 Durability, tensile strength, and fracture load of pellets made from radio frequency pretreated barley straw grind

Temperature (°C)	NaOH concentration (%)	Hammer mill screen size (mm)	Durability (%)	Tensile strength (MPa)	Fracture load (N)
40	1	1.6	71.66 (9.13)	1.17 (0.43)	27.12 (10.12)
50	1	1.6	76.27 (10.55)	1.21 (0.34)	28.12 (7.94)
60	1	1.6	74.18 (8.81)	1.29 (0.51)	30.08 (11.85)
40	0.5	1.6	68.29 (13.73)	0.87 (0.24)	20.19 (5.51)
50	0.5	1.6	61.02 (9.54)	0.86 (0.41)	19.96 (9.56)
60	0.5	1.6	66.94 (12.22)	0.84 (0.50)	19.61 (11.59)
40	1	0.8	78.69 (14.98)	1.07 (0.48)	24.88 (11.11)
50	1	0.8	73.50 (9.95)	1.17 (0.45)	27.12 (10.43)
60	1	0.8	73.08 (5.98)	0.95 (0.28)	22.03 (6.51)
24	1	0.8	67.91 (9.52)	1.15 (0.39)	26.67 (9.11)
24	0.5	0.8	65.74 (4.89)	0.46 (0.17)	10.59 (3.92)
24	0	0.8	63.83 (10.12)	0.29 (0.10)	6.78 (2.29)
24	0	1.6	67.79 (8.98)	0.33 (0.07)	7.79 (1.63)

Values in parentheses = standard deviation; n = 10

Figure 2. Pellets produced from the pretreated biomass using single pelleting Instron machine.

Tensile strength Table 5 shows the tensile strength values of the pellets. Again RF pretreated with 1% NaOH concentration produced pellets with higher tensile strength. The already released or broken down lignin binder helped in the particle binding mechanisms and behavior. The 1% NaOH RF pretreated sample enhanced the creation of the mechanical interlocking of the biomass particles and supported the strength of the bonds between the adhering partners upon application of pressure and temperature. The linear regression analysis shows that concentration and particle size has significant effect on tensile strength and fracture load.

Pellet density and dimensional stability Table 6 shows the density and % density change values of the pellets. Samples pretreated with 1% NaOH concentration has higher density because the released lignin binder enhanced the mechanical interlocking of the particles, increases adhesion between the particles, favors the generation of the intermolecular bonds within the contact area of the biomass particles. When biomass is subjected to heat, lignin tends to become soft, melts and exhibits thermosetting binder resin properties to produce pellets with high density and dimensional stability. Concentration also has significant effect on density. The positive and negative % density change corresponds to diametric and longitudinal contraction and expansion, respectively, of the pellets after two weeks of storage.

Table 6 Pellet density and change during 2 weeks of storage of pellets from radio frequency pretreated barley straw

Temperature (^{o}C)	Concentration (%)	Particle Size (mm)	Density1 (kg/m^{3})	Density2 (kg/m^{3})	% change in density
40	1	1.6	1234.80 (22.95)	1245.34 (21.22)	0.85
50	1	1.6	1270.88 (35.51)	1270.38 (17.96)	-0.04
60	1	1.6	1230.48 (26.60)	1205.11 (22.24)	-2.11
40	0.5	1.6	1138.71 (53.15)	1143.61 (39.84)	0.43
50	0.5	1.6	1065.50 (11.80)	1070.68 (18.00)	0.48
60	0.5	1.6	1085.60 (23.82)	1088.79 (23.51)	0.29
40	1	0.8	1192.95 (20.00)	1129.02 (180.43)	-5.66
50	1	0.8	1214.29 (19.96)	1202.52 (21.10)	-0.98
60	1	0.8	1190.30 (21.41)	1192.51 (11.57)	0.19
24	1	0.8	1188.58 (13.47)	1170.07 (15.32)	-1.58
24	0.5	0.8	969.34 (27.09)	973.92 (23.61)	0.47
24	0	0.8	988.47 (23.82)	1013.53 (37.36)	2.47

Values in parentheses = standard deviation; n = 10, Density1 = density of pellets immediately after the pelleting & Density2 = density of pellets after two weeks of storage.

CONCLUSION The applicability of radio frequency technique as a pretreatment method of lignocellulosic biomass has been investigated. The analysis depicts that 1% NaOH concentration has a significant effect in the deconstruction of the lignocellulosic matrix. This helps in the easy

accessibility and digestibility of the energy potentials and also enhances the production of better, durable and dimensionally stable pellets. The use of NaOH during the RF pretreatment leads to increase in ash content of the pretreated samples.

Acknowledgements The authors acknowledge the support of the technical support unit of the department.

REFERENCES

Balakrishnan, P.A., N. Vedaraman, V.J. Sunder, C. Muralidharan, S. Saminathan. 2004. Radio frequency heating-a prospective leather drying system for future, *Dry Technology*. 22, 1969-1982.

Chandra, R. P., R. Bura, W. E.Mabee, A. Berlin, X. Pan, J. N. Saddler, 2007. Substrate Pretreatment: The Key to Effective Enzymatic Hydrolysis of Lignocellulosics? *Advances in Biochemical Engineering/Biotechnology* 108: 67-93.

Demirbas, A., M. Fatih, M. Balat, H. Balat. 2009. Potential contribution of biomass to the sustainable energy development. *Energy Conversion and Management* 50, 1746-1760

Fan, L. T., L. Yong-Hyun and M. M. Gharpuray. 2006. The Nature of Lignocellulosics and their Pretreatments for Enzymatic Hydrolysis. *Advances in Biochemical Engineering/Biotechnology*, Volume 23, 157-187.

Fiona, J. W., P. Egginton, E. Barrow, C. Desjarlais, H. Hengelveld, D. S. Lemmen, and G. Simonet. 2007 Chapter 2, Background Information: Concepts, Overviews and Approaches. From Impacts to Adaptation: Canada in a Changing Climate, 2007, http://adaptation.nrcan.gc.ca/assess/2007/pdf/ch2_e.pdf

Granada, E., L. M. López-González, J. L. Míguez and J. Moran. 2002. Fuel lignocellulosic briquettes, die design and products study. *Renewable Energy* 27: 561-573.

Izadifar, M., O.D. Baik, G.S. Mittal. 2009. Radio frequency-assisted extraction of podophyllotoxin: Prototyping of packed bed extraction reactors and experimental observations. *Chemical Engineering and Processing* 48, 1437-1444

Mani, S., L. G.Tabil, S. Sokhansanj. 2006. Specific energy requirement for compacting corn stover. *Bioresource Technology* 97, 1420–1426

Mohammad, J. T. and K. Karimi. 2008. Pretreatment of Lignocellulosic Wastes to Improve Ethanol and Biogas Production: A Review. *International Journal Molecular Science* 9, 1621-1651

Punidadas, R., D. Chantal, K. Tatiana, H. S. Ramaswamy, and G. B. Awuah. 2003. 'Radio Frequency Heating of Foods: Principles, Applications and Related Properties-A Review', *Critical Reviews in Food Science and Nutrition*, 43: 6, 587-606.

Ryynanen S. 1995. The Electromagnetic Properties of Food Materials: A Review of the Basic Principles. *Journal of Food Engineeting* 26, 409-429.

Sluiter, A., B. Hames, R. Ruiz, C. Scarlata, J. Sluiter, D. Templeton, and D. Crocker. 2007. National Renewable Energy Laboratory, Laboratory Analytical Procedure (LAP). Determination of Structural Carbohydrates and Lignin in Biomass

Tabil, L., 1996. Binding and pelleting characteristics of alfalfa. Ph.D. thesis. Saskatoon, Saskatchewan: Department of Agricultural and Bioresource Engineering, University of Saskatchewan.

Zhang, Y. H. P. 2008. Reviving the carbohydrate economy via multiproduct lignocellulose biorefineries. J. Ind. Microbiol. Biotechnology. 35, 367-375.